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DEVELOPMENT OF AN INSTRUCTIONAL PROGRAM FOR PRACTICING ENGINEERS HAZARD I USERS

Jonathan R. Barnett

Worcester Polytechnic Institute
Center for Firesafety Studies
Worcester, MA 01609

and

Craig Beyler

Fire Science Technologies
Columbia, MD 21044

Sponsored by
U.S. DEPARTMENT OF COMMERCE
National Institute of Standards
and Technology
Center for Fire Research
Gaithersburg, MD 20899

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Notice

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DEVELOPMENT OF AN INSTRUCTIONAL PROGRAM FOR PRACTICING ENGINEERS HAZARD I USERS

NIST/CFR Grant No. 60NANB9D0949
Final Report

Assistant Professor Jonathan R. Barnett
Center for Firesafety Studies
Worcester Polytechnic Institute
Worcester, MA 01609

Dr. Craig Beyler
Fire Science Technologies
Columbia MD 21044

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Abstract

With the release of **HAZARD I**, a prototype hazard assessment method and software, the National Institute of Standards and Technology (NIST) has brought to the fire protection engineering community a new generation of hazard analysis capabilities. In order to help **HAZARD I** users benefit from the software, Worcester Polytechnic Institute (WPI) has developed a five day short course. The short course emphasizes correct use of the software, and how to recognize misuse.

The course has been offered three times to a broad range of students. In general, only those students with an engineering background were able to learn enough about the **HAZARD I** software to feel that they could continue to learn how use the software on their own and eventually use it in practice. Nonetheless, virtually all of the students benefited from the course and found it a worthwhile experience.

The course development was sponsored in part by the Center for Fire Research of the National Institute of Standards and Technology. Mr. Richard Bukowski was the Scientific Officer.

Contents

1 INTRODUCTION 1

2 COURSE GOALS AND OBJECTIVES 3

3 COURSE CONTENT AND ORGANIZATION 6

4 COURSE MATERIAL 15

5 COURSE EVALUATIONS 16

6 INSTRUCTOR QUALIFICATIONS REQUIREMENTS 20

7 ALTERNATE PRESENTATION MODES 23

8 VALUE FOR DIFFERENT USER GROUPS 25

9 CONCLUSION 29

A HAZARD I COURSE SCHEDULE OUTLINE 31

A.1 DAY 1 31

A.2 DAY 2 33

A.3 DAY 3 34

A.4 DAY 4 36

A.5 DAY 5 37

B STUDENT BACKGROUND FORM 39

C COURSE EVALUATION FORM 42

D COURSE EVALUATION FORM RESULTS 46

D.1 PART IA – THE INSTRUCTORS 46

D.2 PART 1B – GENERAL PERSPECTIVES 48

D.3 PART 1C – SPECIFIC PERCEPTIONS 49

E COURSE NOTEBOOK CONTENTS 51

1

INTRODUCTION

With the release of **HAZARD I**, a prototype hazard assessment method and software, the National Institute of Standards and Technology (NIST) has brought to the fire protection engineering community a new generation of hazard analysis capabilities. This package brings a methodology and supporting software to the desks of practicing engineers which has previously been unavailable to the FPE community. This landmark release presents major educational challenges to practicing engineers who have not in the past used fire modeling of formal hazard analysis methodologies.

In response to these educational challenges, the Center for Firesafety Studies at Worcester Polytechnic Institute has developed a prototype short course for practicing engineers to prepare them to use the **HAZARD I** methodology. The five day short course provides an efficient and effective introduction to the **HAZARD I** methodology and software.

2

COURSE GOALS AND OBJECTIVES

The short course is intended for new and prospective users of **HAZARD I** to introduce them to the software, the underlying principles, and the overall hazard evaluation methodology. The goal is to assist te course participants in overcoming the initial barriers to effective and efficient use of **HAZARD I**, and to develop a sufficient base of knowledge to allow the use to continue to develop as a **HAZARD I** user after the short course.

The course, as any course concerning a tool like **HAZARD I**, needs to go well beyond the mechanics of using the software. The course must focus on how to use the methodology and software correctly and efficiently, and how to recognize misapplications of the software. Any course which focuses largely on the mechanics of using the software will simply make the software accessible to individuals who have not been trained in the appropriate and correct use of the software. In this course the mechanics of using the software are treated as secondary to understanding the basis of the software and the use of the models and methodology.

In order to achieve these goals the course topics include

- the hazard analysis process,
- the scientific basis of the models,
- the limitations and accuracy of the models,
- determination of te required model inputs, and
- the use of the programs.

While participants cannot become expert in any of these areas within the context of a short course, it is important that they be aware and familiar with the details of the models which underlie the **HAZARD I** software. This will allow the user to apply the methodology more effectively and to recognize the extent to which the user's skills and knowledge impact the quality of the results. The most important outcome of the course are the participant's ability to use the software and the appreciation of what the participant and **HAZARD I** are not able to accomplish.

3

COURSE CONTENT AND ORGANIZATION

The role of **HAZARD I** is to facilitate the systematic evaluations of hazards presented in a building. The components of such an analysis include

- problem definition,
- scenario selection,
- model input determination,
- hazard calculations,

- sensitivity analysis and
- consequences analysis.

These aspects of the process are covered through a combination of lectures and small group laboratory work. This approach effectively and efficiently introduces the students to the process and the synthesis inherent in the hazard analysis process.

The outline of the five day course is shown in Figure 1. Further details on individual topics are included in Appendix A. The course is presented as a balance between lectures, demonstration laboratories and independent laboratory project work. The course is organized to maximize the students' actual exposure to the software as well as the overall methodology. In addition to following along at their own computer with the instructors as they present and discuss examples, students complete an independent project during the course of the week. Participants do this independent project work in pairs and report their results and problems daily. Through this interactive process each student actually uses all parts of the software on a problem of personal interest. In addition, through class presentations the participants learn about a wide range of problems and issues which arise in other partic-

HAZARD I SHORT COURSE SCHEDULE

January 1990

Saturday	Sunday	Monday	Tuesday	Wednesday
830-920 Introduction to the Short Course CLB	830-920	830-920 FAST(7) Running FAST JRB	830-920 TENAB(2) CLB	830-920 Course Evaluation
925-1015 Firepower Example JRB	925-1015	925-1015 Project FAST Input (Lab)	925-1015 TENAB-use (Lab) CLB	925-1015 Project Work Session (Lab)
1015-1035 BREAK	1015-1035 BREAK	1015-1035 BREAK	1015-1035 BREAK	1015-1035 BREAK
1035-1125 Firepower Example (cont.) JRB	1035-1125 FAST(3) Fluid Flows CLB	1035-1125 FASTPLOT (Lab) JRB	1035-1125 EXITT(1) CLB	1035-1125 Project Work Session (Lab)
1130-1220 Firepower Example (cont.) JRB	1130-1220 FAST(4) Model Inputs JRB	1130-1220 FAST(8) Review CLB	1130-1220 Project TENAB (Lab)	1130-1220 Project Work Session (Lab)
1220-120 LUNCH	1220-120 LUNCH	1220-120 LUNCH	1220-120 LUNCH	1220-120 LUNCH
120-210 Firepower Example (cont.) JRB	120-210 FAST(5) Heat Transfer CLB	120-210 Project Running FAST (Lab)	120-210 EXITT-use (Lab) input file generation JRB	120-210 Project Project Presentations
215-305 FAST(1) Phenomonology CLB	215-305 FAST.IN (Lab) JRB	215-305 Interum Project Presentations	215-305 Interum Project Presentations	215-305 Project Project Presentations
305-320 BREAK	305-320 BREAK	305-320 BREAK	305-320 BREAK	305-320 BREAK
325-415 FAST(2) Combustion CLB	325-415 Project FAST Input (Lab)	325-415 TENAB(1) CLB	325-415 DETACT MLTFUEL CLB	325-415 Example Uses of Hazard I JRB
420-510 Project Discussion (Lab) JRB	420-510 FAST(6) Fire Scenarios, RHR CLB	420-510 Project Model Refinement (Lab)	420-510 Project EXITT (Lab)	420-510 Advanced Use of Hazard I JRB

Figure 3.1: Figure 1 – COURSE OUTLINE

ipants' projects.

The course makes significant use of examples and student project work to both motivate the participants as well as focus them on problems and issues they will ultimately encounter in their later use of **HAZARD I** in their work. **HAZARD I** is first introduced in the context of a concrete example. The example used is the single family home used in the *Fire Power* video developed by the National Fire Protection Association for instructional purposes. It was decided not use the examples provided in the documentation for two specific reasons. First, it is desirable to expand the number of examples available to the students. More important, it is essential to provide the students with well documented examples. The examples included with the **HAZARD I** package are not documented well enough for instructional purposes. The examples include the input data used, but no discussion of how and why the data was selected. The results are presented, but there is no discussion of how the results relate to the problem being solved. As such, these examples do not address many of the more important concepts which need to be addressed in the context of a course.

Early in the first day of the course the *Fire Power* video is shown and the scenario is discussed in the context of the hazard analysis process. Students are involved in discussions of the types of problems and issues which arise in residential buildings like the one in the video. This broadens the discussion into the general aspects and components of hazard analysis while focusing the students' attention on a concrete and real fire situation.

During the first day a full example based on the *Fire Power* test is demonstrated and discussed by the instructors. While the instructors demonstrates the use of the various programs the students use their own computers to view program elements and enter data. This process quickly involves the students in the problem solving process while familiarizing them with the **HAZARD I** interface shell. The problems and issues which arise in the selection of input data are discussed the the students quickly become aware of their central role in obtaining usable results from the package.

The use of the *Fire Power* example on the first day was not a part of the first course offerings done in August 1989. The original course plan used lectures to introduce the hazard analysis process, an overview of **HAZARD I** and the components of **HAZARD I**. While these lectures included the necessary material, the students felt too passive and the discussions were not sufficiently applications oriented according to most of the students. The *Fire Power* demonstrations cover the same material in a way which involves students directly and motivates them in a way that lectures cannot.

Having been exposed to the whole **HAZARD I** package and process, the course begins to focus on the specific content and basis for the various program elements, beginning with FAST. The FAST model is first presented in phenomenological terms. All of the physical and chemical processes included in FAST are discussed without the use of equations. This gives an overview of FAST and prepares the students for the detailed discussions.

Three lectures on combustion, fluid flows and heat transfer follow the introduction. These lectures cover the submodels included in FAST and examine the accuracy of the models used in light of the state-of-the-art. Emphasis is placed on understanding the submodels, the limitations of our current knowledge, and how these limitations affect our ability to model fire effects. These lectures are given on the first and second days of the course.

Early in the second day, the student project groups present to the class and instructors the problem they will be addressing in their project work. This reporting requirement quickly focuses the two person project teams to define a concrete problem and at the same time exposes the whole class to a range of possible uses of **HAZARD I** which they might not have considered themselves. In general there is some further need for the instructors to narrow or otherwise focus project plans at this stage.

On the second day the participants begin project work in earnest. During the scheduled project periods the project teams will by the end of the week have developed input and run all programs in the **HAZARD I** package several times. During these sessions the two instructors answer specific questions and guide project teams through their work. In addition, two specific lectures are devoted to developing input for the FAST model.

By the third day the project teams are running FAST. Depending on the complexity of the problem, runs may take an hour to finish on a 80286 PC. Time during lunch is provided for such long run times. More complex problems require overnight to complete. Even shorter runs require significant run times. As a result, project teams (groups of two students) are encouraged to make use of both computers at their disposal. This allows the development of new input data on one computer while a FAST run is being completed on the other computer.

The project teams make their first progress report on the third day and sessions on FASTPLOT and TENAB are presented by the instructors. FASTPLOT is introduced through a demonstration lecture and TENAB is introduced in a lecture format. Finally, a review lecture on FAST is presented. The review session on FAST includes a discussion of how to critically evaluate FAST output and a review of the components of FAST. In this review, the class is asked to identify the assumptions and the submodels used in FAST and to classify them as either:

1. well established theory,
2. empirical,
3. approximation.

A homework assignment is made for the evening of the third day in which the students are given a FAST output file and are asked to describe the fire scenario and the resulting fire. In addition, the students are asked to identify any problems with the results and to suggest remedies for the problems. In addition, the students are asked to evaluate the flow field maps provided in the output. The first session of the fourth day is devoted to discussing the homework.

On the fourth day the tenability model lecture is completed and the class is introduced to the TENAB software by use of a lecture demonstration. The EXITT model is addressed and the construction of an input file for EXITT is demonstrated in a laboratory format. DETACT and MLTFUEL are discussed and demonstrated. Finally, the project teams present their progress to date.

The morning of the final day is devoted almost entirely to project work. This is necessary to allow the project teams the time necessary to complete the use of all program elements and refine, in part, their initial runs. Participants also complete a course evaluation form.

The final afternoon is dedicated to final project presentations and the introduction of advanced topics. The project presentations give an overview of the broad range of topics that may be analyzed using the **HAZARD I** package. Afterwards, additional topics not discussed as part of the team project presentations, are presented. This is followed by a presentation and demonstration of advanced topics on the use and limitations of the **HAZARD I** package. This is an important part of the course as it emphasizes that the five day short course only includes basic topics. Hopefully, the participants will realize the need to continue learning how to use the **HAZARD I** package on their own.

4

COURSE MATERIAL

A course notebook is given to each student. The contents of the notebook are used as overheads during the lecture sessions. The overheads are reproduced in the notebook to simplify note taking and provide a notebook which has additional value to the student as a reference volume which supplements the three volumes of demonstration provided with the software. The contents of the notebook, in a slightly modified form, are included in Appendix E.

5

COURSE EVALUATIONS

At the beginning of the course, each participant is asked to complete a questionnaire to establish each student's background and course expectations (see Appendix B). These questionnaires are evaluated by the instructors during the lunch time break of the first day. Student expectations, as stated on page two, are closely examined. Where expectations are outside the scope of the course, students are spoken to on an individual basis to prevent any misunderstanding of what will be taught. The course questionnaires may also be used to help form project teams. For example, it is beneficial to put a person with computer experience together with a student who doesn't have much experience.

5. COURSE EVALUATIONS

The other purpose of the entry questionnaire is to help the students focus on what they hope to learn from the course. This helps to create a positive learning environment.

On the final day of the course, course participants fill out a course evaluation form. The form used for the short course was derived from the evaluation form used for regular courses taught at WPI (see Appendix C). This incorporates much of the well researched general questions which are relevant to a wide range of courses. For instance, the instructor evaluation section used for this course was exactly as used in the regular WPI course evaluation form. This allows some comparison of the course responses with other courses taught at WPI. Other questions in the course evaluaton are specific to this short course. While these cannot be directly compared with responses for other courses, they provide information of direct relevance to this course.

The results of the course evaluation varied for each of the three times the short course was offered. Based on student comments, the course was changed until it evolved into the course described in this report. A numerical summary of the course evaluation for the third course is included in Appendix D. The section on the instructor(s) indicates that the course instructors were very good. When the ratings are compared to the overall WPI average, the instructors are in the second from the top quintile of all instructors at WPI.

The student's general perspectives were very positive. The strongly positive response to the WPI handout material indicates the need for such material. The poor response to the NIST documentation was probably a reflection of the limited use of the NIST documentation during the course. In general, the facilities rated quite well, although there were some negative comments about the computer projection equipment. There doesn't appear to be a simple solution to this problem.

Most students seemed challenged by the course content, however approximately the same number of students felt that the course was too long as those that felt it was too short. Overall, most felt that they learned a lot from the course.

The results of the section on "Specific Perceptions" showed a lack of consensus among the students as reflected in a high standard deviation. For example, the average score on the question "On the basis of this course I will be able to continue to develop hazard analysis skills" was 3.143 (based on a maximum of 4.0, indicating that most students would be able to continue learning on their own. However, the standard deviation was 1.027. This reflected the split between the 1 person who rated the question a 0, the 8 who rated it 3 (Agree) and the 5 who rated it 4 (strongly agree).

It is also interesting to note that although the question "I learned a lot in this course" recieved a score of 3.5, the question "I will now be able to successfully use **HAZARD I** at my current job" received an average rating of 2.571, with a standard deviation of 1.158. This low rating was based on 2 "Not applicable", 1 "Disagree", 10 "agree" and 1 "strongly agree". In general, students with engineering backgrounds felt more confident about using **HAZARD I** than non-engineers, although both groups felt that they had learned a lot during the course.

6

INSTRUCTOR QUALIFICATIONS REQUIREMENTS

The experience gained in this course clearly indicates the need to utilize instructors whose expertise goes well beyond the software itself. The instructors need to be familiar with the models underlying the software and need to be able to relate and contrast these models with the broader literature in fire dynamics, people movement, and tenability analysis. The limitations of the software cannot be given appropriate coverage if the instructor is not familiar with the research literature in these areas.

The instructors also need to have significant experience in evaluating output from models like **HAZARD I**. It is entirely possible for the output to appear superficially reasonable, while the results are in fact not even plausible. Thus, the output from the modes needs to be closely studied and the interactions between variables needs to be found and understood. This is because it is essential that the students learn to identify which submodels are being used and their impact on the ultimate results.

It is also very important that the instructors be familiar with hazard analysis methods and problem solving methods in firesafety engineering. Reality cannot be fully captured in any single computer run. Major uncertainties exist in the fires to be anticipated and the expected condition of the building at the time of the fire. This is in addition to all the uncertainties dictated by the state-of-the-art as implemented in **HAZARD I**. These considerations mean that there is a great deal of need to interpret and integrate the results of a large number of computer calculations in the context of the problem to be solved. Unfortunately, it is all too easy to get so involved in the details of running the software that these essential aspects can easily be overlooked.

6. INSTRUCTOR QUALIFICATIONS REQUIREMENTS

Finally, a short course of this type is very challenging for both students and instructors. It is very important that teaching methods be used which capture the imagination of the students and motivate them to work through the many frustrations which inevitably arise in learning such a tool as **HAZARD I**. This is especially true in a concentrated short course environment. The course needs to be both fun and challenging. Student involvement through project work and homework is essential to success in this type of course.

7

ALTERNATE PRESENTATION MODES

The experience gained through three presentations of this course indicates the importance of individual interaction of the participants with the computer and the instructor to a successful course. It would be impossible to effectively teach this course without a computer laboratory and some ability to interact with the instructor.

Thus, while portions of the course could be effectively videotaped, there will always need to be a trained instructor directly available to the students in a computer laboratory environment. However, it is possible that a satellite course delivery system could be effective. Using this method of delivery there is direct opportunity for students to interact with an instructor located at a remote location. As such, it may be sufficient to use a previously trained **HAZARD I** user as a laboratory monitor at each reception site. the most obvious reception sites are local universities which are already equipped for satellite course delivery.

It remains to be seen if the demand for course delivery is sufficiently high to justify pursuing remote course delivery systems. To date, there does not seem to be sufficient demand.

8

VALUE FOR DIFFERENT USER GROUPS

While the course was originally designed for fire protection engineers, the classes held to date included many non-fire protection engineers and many non-engineers. It was found that most groups could benefit from the course, though what each group learned differed markedly.

In general, the engineers were better able to understand the basis of the models and their limitations. As such, they tended to get better results from the program and were able to be more critical of the results. However, such success was not universal, indicating that some of the engineers did not gain a successful understanding of the bases of the models. It would be fair to say that an engineering background did not guarantee that **HAZARD I** would be used effectively. This was particularly true for those engineers who were new to fire or who did not use quantitative tools in their daily work. In fact there was a subgroup of engineers who did not currently use fire modeling and who did not wish to understand the basis of the models and resented being exposed to such details. Clearly, this type of attitude presents a severe barrier to students becoming effective users of **HAZARD I**.

The fire service students were able to learn to use the program. However, several had severe difficulty largely due to their lack of computer skills. While the rest of the class was learning to use the models, these students were also learning to use the computer. The result was that they did not learn to use the models. While a high level of computer skills is not required to use **HAZARD I**, its is very important to have basic skills in the use of the keyboard in order to interact with simple programs.

In general, even when use of the computer was not an impediment, the fire service personnel found it impossible to understand the basis of the FAST model. Nonetheless, they avidly paid attention during these lectures and fully appreciated the importance of understanding the basis of the programs in order to use the models effectively.

In the end, most fire service students did not think they could use **HAZARD I** as a quantitative tool. They did think it might be useful for training fire service personnel about fire and how fire ground actions may affect fire and smoke behavior. They also spoke of potential for use of the model for public education; for example, to teach the public about the value of smoke detectors and closing bedroom doors.

Code officials did not fully understand the basis of the models and as such could not correctly use the models to predict fire, smoke and people behavior. However, they were able to learn enough about the models to evaluate many aspects of the use of **HAZARD I** by individuals who presented results to them. They were able to ask questions which would indicate whether the submitter actually understood the model results and the limitation of the models themselves. It would seem quite realistic to expect to be able to train code officials to evaluate, at least in a preliminary fashion, the results of a **HAZARD I** analysis presented to them as the basis of a code exception or modification.

Although code officials can be trained to perform a preliminary evaluation of **HAZARD I** output, it is highly likely that a detailed evaluation would require consultation with an engineer.

The non-engineer fire investigators who have taken the course to date, in general fall in the same category as the fire service. They were able to use the models, but were not effective in using the models for anything more than demonstration of a known principle, such as the effectiveness of smoke detectors. For both the investigators and the fire service, the common problem was that their level of understanding of the basis of the models did not allow them to identify improper or inappropriate use of the models.

In all cases, educational background or job experience were no guarantee of success in using **HAZARD I**, unless skills similar to that needed for the use of **HAZARD I** were regularly used in daily work. Thus, while many engineers were quite successful in using the package, others were not so successful. In all cases, it is clear that continued use of the package and self-study beyond the five day short course is needed for students to develop into effective users of the methodology. No follow-up study has been undertaken to evaluate the extent of such activities among the participants in the first three classes.

9

CONCLUSION

WPI has developed a short course to teach users how to use **HAZARD I**. The short course emphasizes how to use the **HAZARD I** methodology and software correctly and efficiently, and how to recognize misapplications of the software. Extensive course materials were prepared as part of this effort. The course has been taught three times, with modifications reflecting the instructors' experiences being added to the course each time.

The course participants have included fire protection engineers, general engineers and researchers, Code officials and members of the fire service. All participants benefited from the course. However, only the engineers, in general, were able to learn enough about **HAZARD I** to continue learning how to use it on their own and eventually use it in practice.

Based on this experience, it is clear that short course such as this one are essential if software as complex as **HAZARD I** is to be used safely and effectively. It may also be concluded that an engineering background is a necessary prerequisite for the successful use of the software.

Appendix A

HAZARD I COURSE SCHEDULE OUTLINE

A.1 DAY 1

A.1.1 Introduction to the Short Course

This session will lay out the course goals and expectations, as well as organizing the class into two person working groups for laboratory and project work. The logistics of the course will be handled. The week's schedule and class methods will be spelled out. This session may not require the full period, leaving some extra time for the next session. Each day will begin with a short informal run down of the plans for the day.

A.1.2 *Fire Power* Example

The use and capabilities of **HAZARD I** will be demonstrated through an example based an actual residential fire as shown in the *Fire Power* videotape. The video will be used to introduce the scenario and show the fire and its results. How **HAZARD I** can be used for this problem will be explored. Through the course of several sessions each of the relevant parts of **HAZARD I** will be demonstrated for the *Fire Power* example case. This will include the development of input sets, running the programs, and examining outputs and comparing the results to both the video and data collected during the test. Students will be working at their PC's following the instructor through this extensive introductory example. This session will begin to expose the students to the methodology and software, its power and limitations.

A.1.3 FAST(1)

Introduction to the general structure and capabilities of FAST; introduce zone model concept; introduce the phenomena which are modeled without using equations; discuss the general validity and accuracy of the model to the extent that validation results are available. This session is intended to make the student aware of the fire phenomena which FAST can handle and the general accuracy which may be reasonably expected under ideal conditions.

A.1.4 FAST(2)

Detailed discussion of the modeling used in FAST including the equations. The discussion will focus on combustion, smoke and gas generation. The models used in FAST will be presented, compared with the state-of-the-art, and discussed in terms of the ranges of conditions for which the model has been tested. The limitations of the models and their possible impact on the results will be discussed.

A.1.5 Project

This session is used to allow students to begin to define projects for use as an exercise through the remainder of the course. Projects will be done in teams of two, with each student having his own PC. The instructors discuss the project definition process and provide informal feedback to the project teams.

A.2 DAY 2

A.2.1 FAST(3)

Detailed discussion of the modeling used in FAST including the equations. The discussion will focus on fluid flows. The models used in FAST will be presented, compared with the state-of-the-art, and discussed in terms of the ranges of conditions for which the model has been tested. The limitations of the models and their possible impact on the results will be discussed.

A.2.2 Project Discussion

This session will be used to define projects for use as an exercise through the remainder of the course. Each team will have previously(overnight) developed a tentative project. Each team will present their project to the class. Questions will be handled and projects will be approved by the faculty during this session.

A.2.3 FAST(4)

Establishing model input data. Defining the building, vents, walls, wind, etc will be discussed. How to simplify a building to allow it to be evaluated, how to select vent and wind conditions, and other matters which need to be addressed in developing FAST input.

A.2.4 Project

Students develop building inputs for their project case and begin to load these using FAST_IN. Emphasis will be placed on the process of input determination and documentation of the basis for input selection.

A.2.5 FAST(5)

Detailed discussion of the modeling used in FAST including the equations. The discussion will focus on heat transfer. The models used in FAST will be presented, compared with the state-of-the-art, and discussed in terms of the ranges of conditions for which the model has been tested. The limitations of the models and their possible impact on the results will be discussed.

A.2.6 FAST_IN

This laboratory session will introduce the FAST_IN program and how it can be used to generate FAST input files. All aspects of program use will be covered such that students are ready to begin entering input for their project case.

A.2.7 Project

Students develop building inputs for their project case and begin to load these using FAST_IN. Emphasis will be placed on the process of input determination and documentation of the basis for input selection.

A.2.8 FAST(6)

Defining fire scenarios and developing fire and species generation inputs. This includes statistical considerations as well as the methods available for determining the heat release rate history for generic fuel items. Specific discussions of the interaction of species generation inputs with the model will be included. Available sources of data will be discussed. A small library of input data sources will be made available to students for use in the laboratory.

A.3 DAY 3

A.3.1 FAST(7)

Running FAST; this session will cover methods for running FAST and for modifying input files generated by FAST_IN. The available outputs from the program will be discussed. An example will be developed from inception through to running FAST. This example will be further developed throughout the course.

A.3.2 Project

In this session the students will complete the basic building inputs and will begin to define scenarios as well as defining the input fires.

A.3.3 FASTPLOT

The use of FASTPLOT will be explored for both graphics and ASCII file generation.

A.3.4 FAST(8)

Review of FAST including capabilities, limitations, options, etc. The example will be further developed including output. Outputs will be evaluated critically to detect any problems or shortcomings of the results.

A.3.5 Project

Students will complete a first cut input file for FAST and run FAST. Remember that each student has a computer, so they can be running FAST on one PC while developing another data set on the other PC.

A.3.6 Interim Project Presentations

Student groups will give a short description of their problems and progress in project work to date. This session is intended to expose the class to the issues which arise in using **HAZARD I** on a wide range of problems.

A.3.7 TENAB(1)

Detailed discussion of the tenability models used in TENAB, including the source of the data underlying the expressions, and a review and comparison of the various models available. The various ways of using TENAB will be discussed and compared.

A.3.8 Project

Students will refine their initial FAST input sets, improving the use of the model and examining relevant scenarios. Students will begin to develop their first EXITT input sets.

A.4 DAY 4

A.4.1 Homework Discussion

The homework assignment for the previous night is reviewed and discussed in class. The assignment involves the evaluation of a FAST output file for the Firepower house which the class has not before seen. Students identify the simulation which is being done, point out notable events in the run, and identify errors, limitations, or problems with the run. The evaluation of the flow maps in the .FST file is discussed.

A.4.2 TENAB Use

The TENAB program will be demonstrated in this laboratory session. The input and output files will be examined. The example will be used to demonstrate the use and interpretation of TENAB output.

A.4.3 EXITT(1)

Discussion of the EXITT model, its structure, assumptions, decision rules, and the interaction of the people and the fire signatures.

A.4.4 Project

TENAB- prepare data and run the program at least once.

A.4.5 EXITT Use

Laboratory session on developing an input file for EXITT. The example will be used as an instructional tool for learning the file structure and how to develop the input file. The program will be run and the results examined.

A.4.6 Interim Project Presentations

Student groups will give a short description of their problems and progress in project work to date. This session is intended to expose the class to the issues which arise in using **HAZARD I** on a wide range of problems.

A.4.7 DETACT, MLTFUEL

The basis of these two auxiliary programs will be discussed in detail and the software will be demonstrated.

A.4.8 Project

Students will develop and run an input set for the EXITT program.

A.5 DAY 5

A.5.1 Course Evaluation

Course evaluation by students. Fill out course evaluation forms and provide feedback.

A.5.2 Project

Completion of student projects. Students will prepare a short paper on the results of their project using the **HAZARD I** text editor. The report will discuss the process and the results obtained. It should be written in the style of a progress report to a supervisor. Copies of any files created by the students may be made with all files created by the students remaining on the hard disk for examination by the faculty after the course ends as an aid in informally assessing the effectiveness of the course.

A.5.3 Project Presentations

Final presentations given by the project teams. These sessions will allow students to describe and discuss with others the successes and problems encountered in the project work. Open for general questions and comments.

A.5.4 Example Use of HAZARD I

Complete the example used throughout the course and review the whole process for the example. Examine what additional work could be done and how **HAZARD I** performed for the example. Critical discussion of **HAZARD I** using the example as a vehicle. Hopefully, the students will have a good sense of what can be expected from the software and the method at this point.

A.5.5 Advanced Use of HAZARD I

The course necessarily focuses on the basics needed to perform an analysis. This session introduces more advanced topics which the students may want to explore in more detail after the course.

Appendix B

STUDENT BACKGROUND FORM

APPENDIX B. STUDENT BACKGROUND FORM

Center for
Firesafety
Studies

HAZARD I

A Short Course on Modeling Fire and Fire Hazards

Course Participants Entry Questionnaire

Student Background

Name:

Job description:

Education and Training(circle one):

1. Fire protection engineer
2. Other engineering field(please specify field)
3, Engineering technology
3. Non-engineer(please specify)

Educational Level(circle one) HS AS BS MS PhD

Are you a member of the Society of Fire Protection Engineers? yes no

Have you taken a college level course in the following areas?

Fluid mechanics	yes	no
Heat transfer	yes	no
Thermodynamics	yes	no
Engineering mathematics	yes	no
Hazard analysis	yes	no
Computer programming	yes	no

Do you have and use an IBM PC compatible computer at work? yes no

APPENDIX B. STUDENT BACKGROUND FORM

If you use a computer at work, describe briefly the types of tasks you routinely perform using the computer and how conversant you are with computers and PC's in particular.

Student Expectations

Do you expect to use HAZARD I in your work after the short course? yes no

If so, what kinds of uses can you now envision? If not, why not?

What level of performance with HAZARD I do expect to achieve by the end of the short course in the following areas:

Understanding the method's capabilities:	novice	average	expert
Running the software:	novice	average	expert
Developing a hazard analysis:	novice	average	expert
Developing input for the software:	novice	average	expert
Interpreting output from the software:	novice	average	expert
Understanding the basis of the method:	novice	average	expert
Understanding the method's limitations:	novice	average	expert
Using the documentation:	novice	average	expert

What do you hope to learn and be able to do at the end of this course?

Appendix C

COURSE EVALUATION FORM

APPENDIX C. COURSE EVALUATION FORM

HAZARD I
A SHORT COURSE FOR FIRE PROTECTION ENGINEERS

COURSE EVALUATION FORM

You have just concluded a pilot course on Hazard I. By providing your perceptions of the effectiveness of the course, you can help to improve its overall quality.

PART I

Please circle the catagory to indicate your feeling of diagree/agree from STRONGLY DISAGREE to STRONGLY AGREE. Circle NOT APPLICABLE if the particular statement does not apply to you.

NA	Not Applicable
SD	Stongly Disagree
D	Disagree
A	Agree
SA	Strongly Agree

PART IA - THE INSTRUCTORS

1. The instructors established clear objectives for this course	NA	SD	D	A	SA
2. The instructors organized the course well.	NA	SD	D	A	SA
3. The instructors were well prepared to teach each class.	NA	SD	D	A	SA
4. The instructors communicated well.	NA	SD	D	A	SA
5. The instructors demonstrated a good understanding of the material being taught.	NA	SD	D	A	SA
6. The instructors used class time efficiently.	NA	SD	D	A	SA
7. The instructors used visual aids in an effective manner.	NA	SD	D	A	SA
8. The instructors stimulated my interest in the subject matter.	NA	SD	D	A	SA
9. The instructors were well above average.	NA	SD	D	A	SA
10. The instructors showed me how to use the computer equipment properly.	NA	SD	D	A	SA
11. The instructors provided adequate time to complete the projects.	NA	SD	D	A	SA

APPENDIX C. COURSE EVALUATION FORM

PART IB - GENERAL PERSPECTIVES

1. The WPI prepared handouts helped me learn the subject matter. NA SD D A SA
2. The NIST prepared Hazard I documentation was useful in learning to use the software. NA SD D A SA
3. The room used for the course was acceptable. NA SD D A SA
4. The computer equipment was in good operating condition. NA SD D A SA
5. The computer projection technique was useful. NA SD D A SA
6. The material to be learned in this course was difficult. NA SD D A SA
7. The one week format was too long. NA SD D A SA
8. The one week format was too short. NA SD D A SA
9. I learned a lot in this course. NA SD D A SA

PART IC - SPECIFIC PERCEPTIONS

1. Hazard I will be useful to me at my current job. NA SD D A SA
2. Hazard I will be useful to use in the future. NA SD D A SA
3. On the basis of this course I will be able to continue to develop hazard analysis skills. NA SD D A SA
4. I will now be able to successfully use Hazard I at my current job. NA SD D A SA
5. I feel confident that I can identify misuse of Hazard I. NA SD D A SA
6. I need an additional course on how to use Hazard I. NA SD D A SA
7. I now can teach the use of Hazard I to others. NA SD D A SA

APPENDIX C. COURSE EVALUATION FORM

PART II - BACKGROUND INFROMATION

1. I am/ am not (circle one) a member in the Society of Fire Protection Engineers.

2. My job Classification is ___________________________.(describe primary job function)

3. I have/have not (circle one) used a PC for engineering analysis in the past.

PART III - WRITTEN COMMENTS

1. What did you particularly like about this course?

2. What did you particularly dislike about this course?

3. Can you suggest anything that the instructors can do to improve the quality of teaching?

4. What strategy would you advise a friend to use to benefit from this course?

5. Other comments?

Appendix D

COURSE EVALUATION FORM RESULTS

(Note: all results based on a maximum score of 4.00)

D.1 PART IA – THE INSTRUCTORS

D.1.1 The instructors established clear objectives for this course:

Average: 3.571, Standard Deviation: 0.514.

D.1.2 The instructors organized the course well.

Average: 3.500, Standard Deviation: 0.519.

D.1.3 The instructors were well prepared to teach each class.

Average: 3.929, Standard Deviation: 0.267.

D.1.4 The instructors communicated well.

Average: 3.643, Standard Deviation: 0.497.

D.1.5 The instructors demonstrated a good understanding to the material being taught.

Average: 3.857, Standard Deviation: 0.363.

D.1.6 The instructors used class time efficiently.

Average: 3.500, Standard Deviation: 0.519.

D.1.7 The instructors used visual aids in an effective manner.

Average: 3.429, Standard Deviation: 0.514.

D.1.8 The instructors stimulated my interest in the subject matter.

Average: 3.643, Standard Deviation: 0.497.

D.1.9 The instructors were well above

average. Average: 3.643, Standard Deviation: 0.497.

D.1.10 The instructors showed me how to use the computer equipment properly.

Average: 3.357, Standard Deviation: 1.082.

D.1.11 The instructors provided adequate time to complete the projects.

Average: 3.429, Standard Deviation: 0.514.

D.2 PART 1B – GENERAL PERSPECTIVES

D.2.1 The WPI prepared handouts helped me learn the subject matter.

Average: 3.286, Standard Deviation: 0.611.

D.2.2 The NIST prepared HAZARD I documentation was useful in learning to use the software.

Average: 2.071, Standard Deviation: 1.072.

D.2.3 The room used for the course was acceptable.

Average: 3.286, Standard Deviation: 0.469.

D.2.4 The computer equipment was in good operating condition.

Average: 3.571, Standard Deviation: 0.514.

D.2.5 The computer projection technique was useful.

Average: 3.143, Standard Deviation: 0.663.

D.2.6 The material to be learned in this course was difficult.

Average: 2.714, Standard Deviation: 0.914.

D.2.7 The one week format was too long.

Average: 2.143, Standard Deviation: 0.535.

D.2.8 The one week format was too short.

Average: 2.214, Standard Deviation: 0.426.

D.2.9 I learned a lot in this course.

Average: 3.500, Standard Deviation: 0.519.

D.3 PART 1C – SPECIFIC PERCEPTIONS

D.3.1 HAZARD I will be useful to me at my current job.

Average: 2.857, Standard Deviation: 1.027.

D.3.2 HAZARD I will be useful to use in the future.

Average: 3.286, Standard Deviation: 0.611.

D.3.3 On the basis of this course I will be able to continue to develop hazard analysis skills.

Average: 3.143, Standard Deviation: 1.027.

D.3.4 I will now be able to successfully use HAZARD I at my current job.

Average: 2.571, Standard Deviation: 1.158.

D.3.5 I feel confident that I can identify misuse of HAZARD I.

Average: 2.929, Standard Deviation: 0.475.

D.3.6 I need an additional course on how to use HAZARD I.

Average: 2.500, Standard Deviation: 0.650.

D.3.7 I can teach the use of HAZARD I to others.

Average: 2.357, Standard Deviation: 0.929.

Appendix E

COURSE NOTEBOOK

CONTENTS

WPI Center for
Firesafety
Studies

HAZARD I

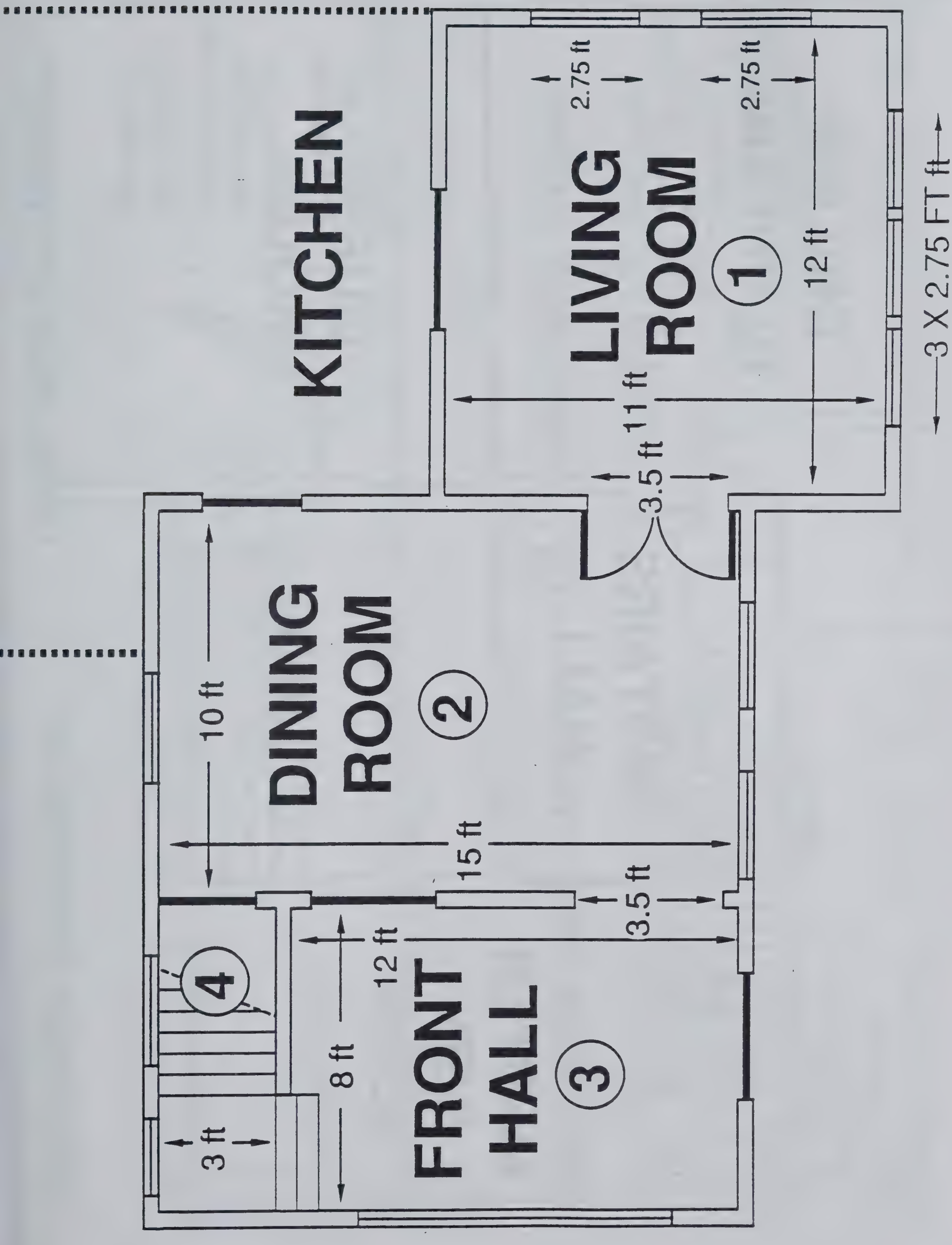
A Short Course on Modeling Fire and Fire Hazards

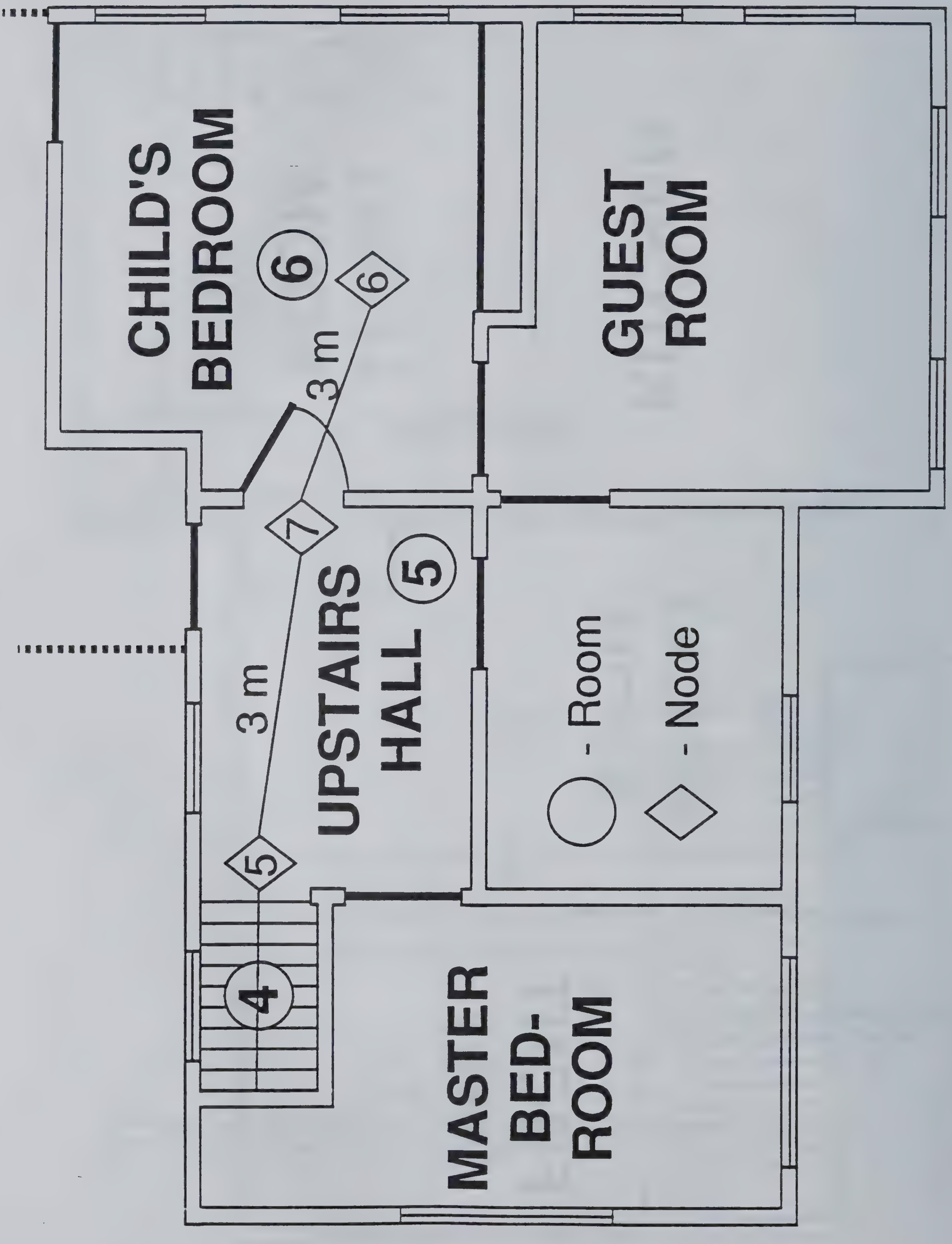
Developed by:

Dr. Jonathan Barnett
Assistant Professor
Center for Firesafety Studies
Worcester Polytechnic Institute
Worcester MA 01609

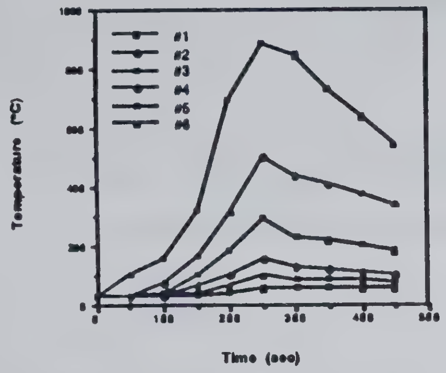
Dr. Craig Beyler
Fire Science Technologies
5430F Lynx Lane
Suite 131
Columbia MD 21044
Adjunct Assistant Professor, WPI
Center for Firesafety Studies

Developed with partial support from the Center for Fire Research, NIST
NIST Scientific Officer: Richard Bukowski


KITCHEN
LIVING ROOM
①
2.75 ft
2.75 ft
12 ft
11 ft
3.5 ft
3 X 2.75 FT ft
DINING ROOM
②
10 ft
15 ft
3.5 ft
FRONT HALL
③
④
12 ft
8 ft
3 ft


CHILD'S BEDROOM
6
6
3 m
GUEST ROOM
7
UPSTAIRS HALL
5
3 m
- Room
- Node
5
4
MASTER BED-ROOM

FIREPOWER Temperatures



- All compartments peak together
- Room of origin well above flashover temp.
- Modest increases on 2nd floor.

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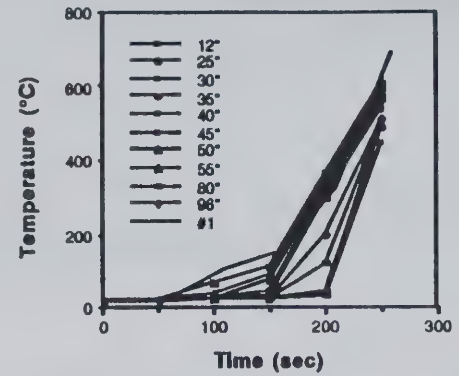
Center for Firesafety Studies

CLB-FP1-1

FIREPOWER Temperatures



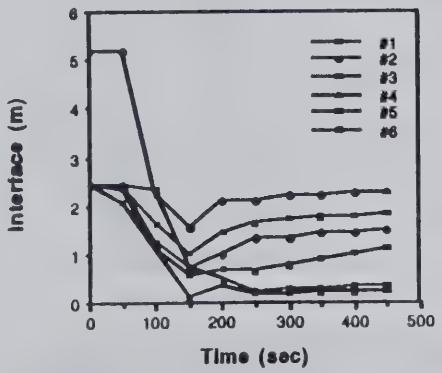
- Calculation is time shifted 60 s.
- Calculation continues to rise.
- Interface nears floor and lower layer contamination starts at 250 s.

1/12/90

Center for Firesafety Studies

CLB-FP1-2

FIREPOWER- Layer Interface



- Layer depth decreases with distance from fire
- Second floor well smoke logged.
- Note behavior in stairway.

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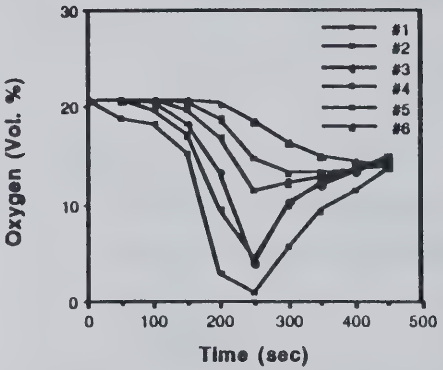
CLB-FP1-3

FIREPOWER- Oxygen



- Fire is never limited by oxygen
- Peak oxygen depletion decreases with distance from fire
- Note profile differences.

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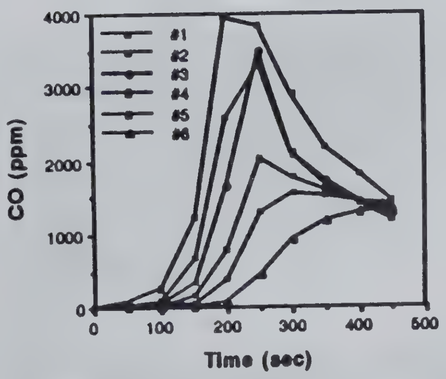
Center for Firesafety Studies

CLB-FP1-4

FIREPOWER- Carbon Monoxide



- CO is never enhanced by oxygen depletion
- Peak CO decreases with distance from fire
- Note CO profile differences.

1/12/90

WPI Center for Firesafety Studies

CLB-FP1-5

The Hazard Analysis Process

Definition

Evaluating the consequences of one or more fire scenarios which represent foreseeable dangerous situations.

The Hazard Analysis Process

Major Components

- Defining the foreseeable fire(s)
- Building, people response
- Consequences

The Hazard Analysis Process

The Fire

- Define fire scenarios- a detailed description of the anticipated fire and the conditions of the building and its occupants. Examples for a hotel room?
- Determine the fire characteristics and the fire environment created.

The Hazard Analysis Process

The Response to the Fire

Response by
- Building and building systems
- Fire protection systems and firefighting forces
- People

The Hazard Analysis Process

Consequences

- People - injuries and deaths
- Properties losses
- Interruption costs/losses

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Comparison with Risk Analysis

Key Components of Risk Analysis

- Combines probabilities of occurrence of events with a measure of the the severity of the consequences.
- Uses a single measure of fire severity
- Considers directly the uncertainty of estimates.

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The Hazard Analysis Process

Uses of Hazard Analysis

- Decision making
- Failure analysis
- As a component of risk analysis

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The Hazard Analysis Process

Decision Making

- Define the decision to be made and the objectives of the analysis (what consequences are to be avoided).
- Define the fire, and evaluate the response and consequences.
- Compare predicted and desired consequences.

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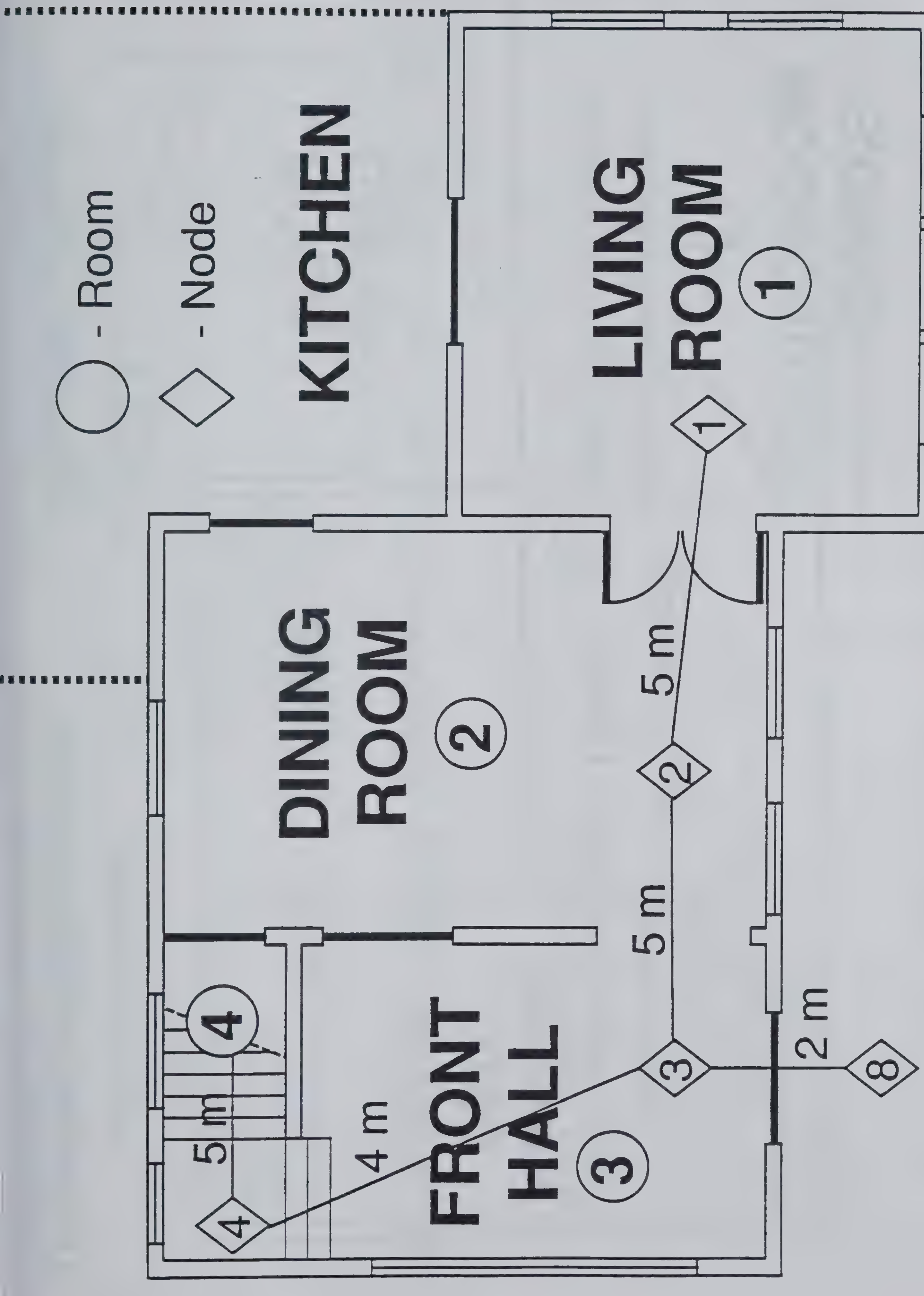
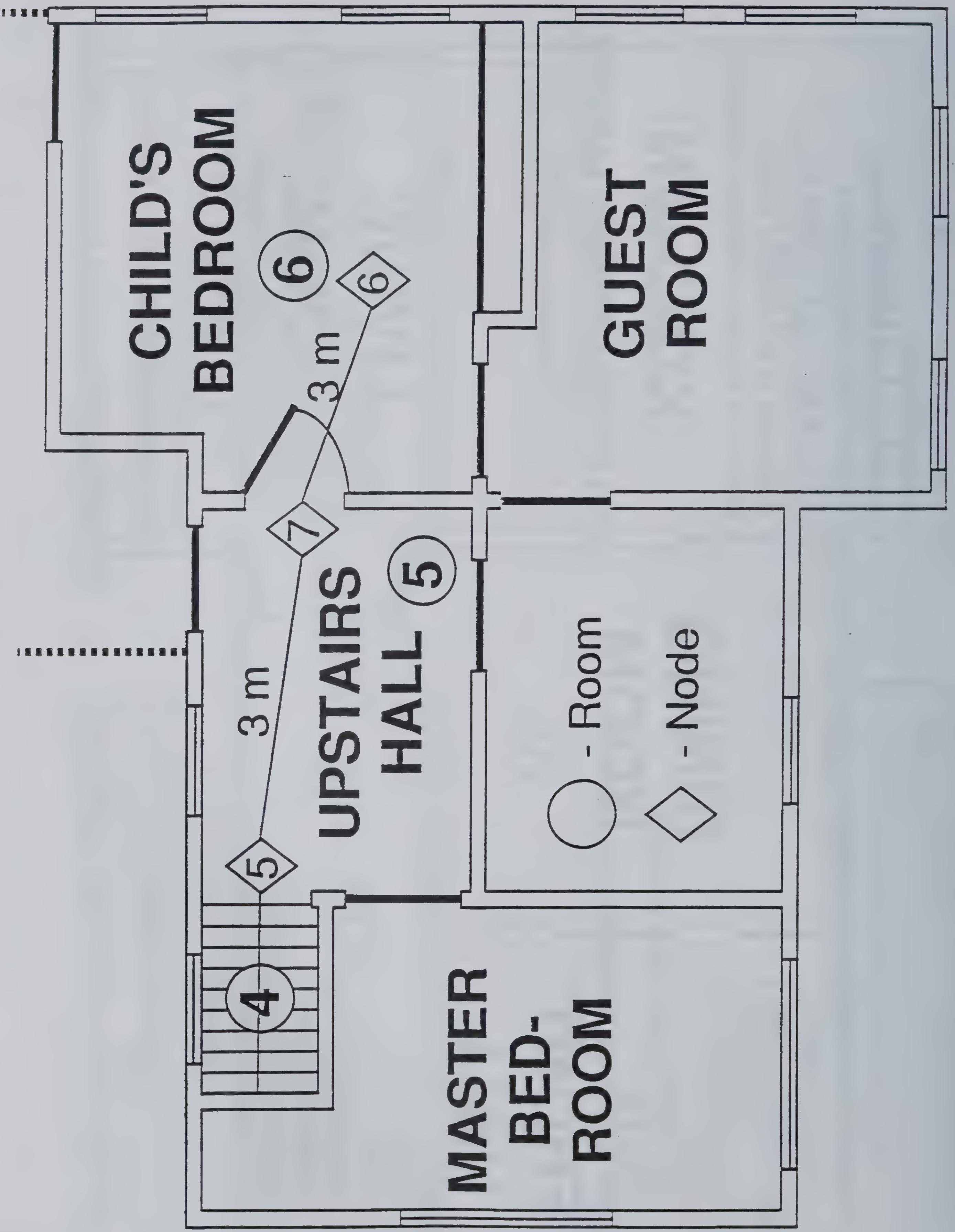

○ - Room
◇ - Node
KITCHEN
LIVING ROOM
①
1
DINING ROOM
②
2
FRONT HALL
③
3
④
4
8
5 m
5 m
5 m
4 m
2 m


CHILD'S BEDROOM
6
6
3 m
7
UPSTAIRS HALL
5
3 m
5
4
GUEST ROOM
MASTER BED-ROOM
- Room
- Node

The Hazard Analysis Process

Hotel Room Examples

- Decision making
- Failure analysis
- As a component of risk analysis

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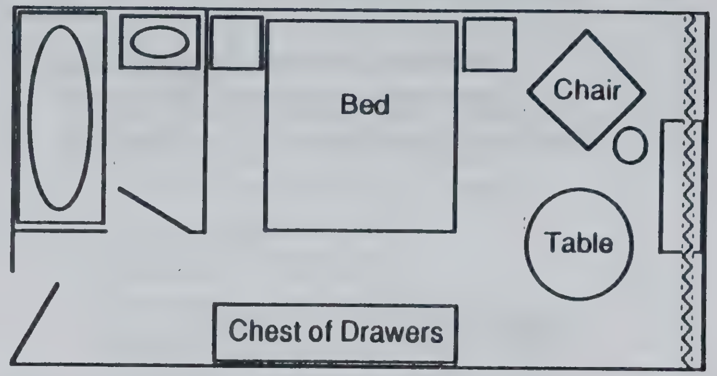
Hotel Room Floor Plan



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Hotel Room Examples

Decision Making

- Decisions ?
- Method ?
- Process ?

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Hotel Room Examples

Failure Analysis (post event)

- Fire event ?
- Hypothesis ?
- Evaluating hypothesis ?
- Establishing critical elements ?

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Hotel Room Examples

Failure Analysis (prior to event)

- **Define failure ?**
- **Scenarios ?**
- **Evaluating scenarios ?**
- **Establishing critical elements ?**

Hotel Room Examples

Risk Analysis

- **Objectives ?**
- **Scenarios ?**
- **Building, people responses ?**
- **Evaluating costs(single measure) ?**

The Hazard Analysis Process

Uses of Hazard Analysis

- **Decision making**
- **Failure analysis**
- **As a component of risk analysis**

The Hazard Analysis Process

Major Components

- **Defining and simulating the fire**
- **Building, people response**
- **Evaluating consequences**

- **Details of methodology may vary with use and objectives.**

The Hazard Analysis Process

HAZARD I

- HAZARD I is a software package designed to assist and structure the hazard analysis process.
- The individual programs are aids to the process, but the user must understand the hazard analysis process to effectively use the package.

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The Hazard Analysis Process

HAZARD I Course Goals

- Understand:
  - The hazard analysis process
  - Capabilities of HAZARD I
  - How to use HAZARD I and documentation
  - Basis of HAZARD I
  - Limitation of HAZARD I
  - How to continue to develop expertise in hazard analysis

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HAZARD I:
A Short Course for FPE's

Goals: Understand the following
- The hazard analysis process
- Capabilities of HAZARD I
- How to use HAZARD I and documentation
- Basis of HAZARD I
- Limitation of HAZARD I
- How to continue to develop expertise in hazard analysis

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HAZARD I Overview

Scope

- Hazard analysis of one and two family dwellings.
- Has limited capabilities outside this scope, but limitations must be closely evaluated.
- Scope is intended to grow over time (pending resources and interest).

HAZARD I Overview

Elements of the Analysis

- Fire - user defined fire and fire products.
- Fire Effects - calculated based on fire and building, including:
  mass flows
  energy transfers
  throughout the building.

HAZARD I Overview

Elements of the Analysis

- Fire Environment-
  temperature
  gas species concentrations
  optical density of smoke
- People Movement - behavior, decisionmaking and exiting.
- Tenability Assessment - effect of heat and toxic gases on building occupants.

Insert fig 1.1 from tech ref.

HAZARD I Overview

User Defined Fire

- User specifies mass and energy output of a single fire source.
- These inputs can only be determined from experiments(empirical knowledge).
- Enhancement of burning due to the fire environment is not calculated.

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HAZARD I Overview

User Defined Fire

- HAZARD I can impose oxygen availability constraints on the fire.
- Fire source representation is very basic: mass loss, energy output, height in room.
- Fire/room interactions will be added in the future.

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HAZARD I Overview

Fire Effects Throughout Building

- Flows: plumes, vent flows, vent mixing.
- Energy transfers: radiation, convection, and conduction involving the fire, hot gases, ceilings, walls, and floors.

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HAZARD I Overview

Fire Environment

- Each room is idealized as being divided into two layers(zone model approach).
- Each layer is assumed homogeneous-
  - temperature
  - gas species concentrations
  - optical density of smoke

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HAZARD I Overview

Occupant Behavior and Movement

- Deterministic behavior rules based on occupant characteristics.
- Occupants respond only to flame and visible smoke, not to toxic gases.
- Available paths for movement are user defined(nodes and arcs).

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HAZARD I Overview

Tenability Analysis

- Effect of fire environment on building occupants as they move through the building.
- Occupants are modeled as moving toxicological receptors.
- Heat, O_2 depletion, CO, CO_2, HCN, CT

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HAZARD I Overview

Elements of the Analysis

- Fire
- Fire effects
- Fire environment
- People movement
- Tenability assessment

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HAZARD I Overview

Scope and Limitations

- Overall scope: one and two family residences.
- Scope of individual parts of the package may be wider than this.
- Working outside the overall scope requires some caution and a good appreciation of the limitations.

Scope and Limitations

Levels of Treatment

- Well established theories.
- Empirical relationships.
- Approximations.

Scope and Limitations

User Defined Fire

- This method is empirically based.
- Experimental methods of value include:
  - room fire experiments
  - furniture calorimeter tests
  - small scale calorimeter tests
- Interactive burning effects are generally thought to only become important as temperatures exceed 500°C.

Scope and Limitations

User Defined Fire

- Oxygen availability and species generation models are immature at this time. Confidence levels are moderate.
- Scope of this section is considerably broader than residential occupancies.

Scope and Limitations

Fire Effects Throughout Building

- Scope of this section is quite broad.
- Experimental and theoretical basis is extensive.
- Confidence
  Within the fire room - mod/high
  On the same floor - moderate
  On other floors - low.
- No HVAC effects, no suppression

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Scope and Limitations

Fire Environment

- Scope of this section is quite broad.
- Based on the previous two sections plus well established conservation equations.
- Confidence - moderate.
- No loss of smoke or HCl to wall surfaces.

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Scope and Limitations

Occupant Behavior and Movement

- Scope: limited to one and two family residences.
- Experimental and theoretical basis is modest.
- Deterministic model enforces stereotypical behavior.
- No effect of toxics on behavior.

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Scope and Limitations

Tenability Analysis

- Scope of this section is quite broad.
- Experimental and theoretical basis is modest- mostly rodent and primate.
- Interactions between toxic gases and between heat and toxic gases are poorly understood.

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HAZARD I Overview

Potential Uses ?

Examples:

1.
2.
3.
4.
5.

HAZARD I Overview

Summary

- HAZARD I is designed for use in performing hazard analyses in one and two family residences.
- Much of the package has utility beyond this scope, but caution is needed.

HAZARD I Overview

Summary

- The quality of the underlying science varies with phenomena.
- Quality is in general sufficient to allow knowledgeable engineers to improve decision making over traditional approaches.

Components of HAZARD I

Introduction

- HAZARD I package contains:
  - 4 primary programs
  - 4 auxiliary programs
- Data transfers between programs are both manual and via files.
- User interface to programs is provided by the menu based HAZARD Interface Shell (HIS).

Components of HAZARD I

Primary Program Modules

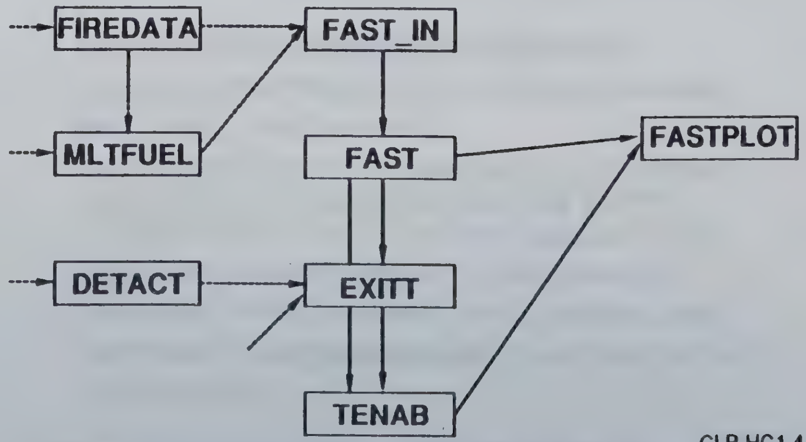
- FAST - fire simulation program
- FAST_IN - generates FAST input file
- EXITT - evacuation model
- TENAB - tenability model

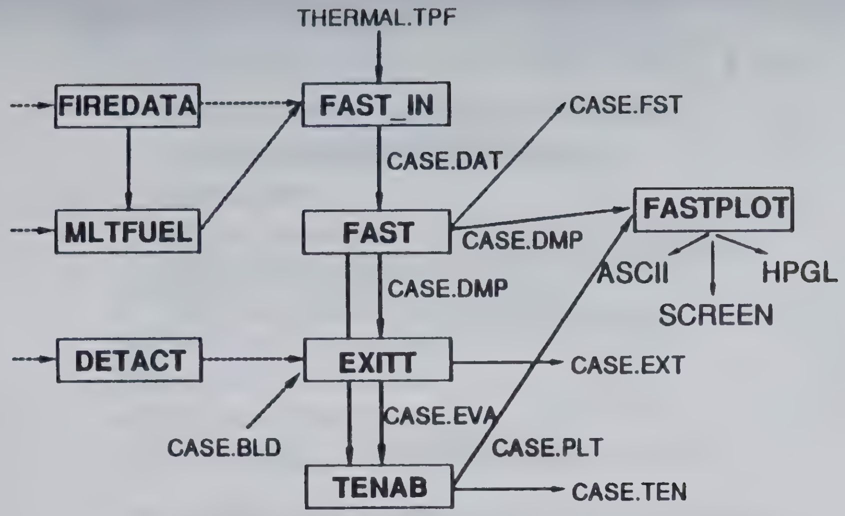
Components of HAZARD I

Auxiliary Program Modules

- FIREDATA - fire properties database
- MLTFUEL - multiple → single fire
- DETACT - detector/sprinkler activation
- FASTPLOT - plotting utility

Modules of HAZARD I





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Components of HAZARD I

FAST

- FAST - Fire and Smoke Transport
- Fire simulation program which includes:
  - fluid flows
  - heat transfer
  - combustion
  - mass and energy balances

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Components of HAZARD I

FAST

- This is the major program of the package.
- Predicts the fire environment to which occupants are exposed:
  - temperatures
  - gas concentrations
  - smoke density

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Components of HAZARD I

FAST_IN

- User interface program to interactively generate the input file required by FAST.
- Inputs are organized into 10 screens each with a help utility to assist in providing the required inputs.

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Components of HAZARD I

EXITT

- Based on a knowledge of the occupants, the building, and the optical density of the smoke, this program simulates the behavior and decision making of occupants while exiting the building.
- Deterministic model - hence stereotypical behavior is modeled.

Components of HAZARD I

TENAB

- Program evaluates the effect of the fire environment on occupants.
- Occupants may be incapacitated or killed by heat and toxic gases.
- Alternate models are used in the program; user may use any of the model results.

Components of HAZARD I

FIREDATA

- This program is a fire database, included in the package for user convenience in finding appropriate input data.
- Current database is modest
- No direct link to other programs.

Components of HAZARD I

MLTFUEL

- FAST accepts only a single fire source.
- MLTFUEL provides a simple approximate method for combining multiple fire sources into a single equivalent source for use in FAST.
- Manual input and printed output only.

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Components of HAZARD I

DETACT

- Predicts the activation of a detector or sprinkler exposed to a ceiling jet flow.
- Can be used for sprinklers and fixed temperature detectors. Smoke detectors are included via a crude analogy.
- Manual input and printed output only.

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Components of HAZARD I

FASTPLOT

- Plotting utility for FAST and TENAB.
- Extracts data from dump files and can provide:
  - screen plots
  - HPGL files for plotters
  - tab delimited ASCII files for printing or interfacing with a spreadsheet or graphics program.

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Components of HAZARD I

Primary Program Modules

- FAST - fire simulation program
- FAST_IN - generates FAST input file
- EXITT - evacuation model
- TENAB - tenability model

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Components of HAZARD I

Auxiliary Program Modules

- FIREDATA - fire properties database
- MLTFUEL - multiple → single fire
- DETACT - detector/sprinkler activation
- FASTPLOT - plotting utility

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Components of Hazard I

HAZARD I Course Goals

- Understand:
  - The hazard analysis process
  - Capabilities of each program module
  - How to use each module and its documentation
  - Basis of each module
  - Limitation of each module
  - How to continue to develop expertise in hazard analysis

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FAST

Fire And Smoke Transport

- Multi-room model - up to six
- Zone fire model - upper(hot) & lower(cold)
- Major variables calculated:
  - temperatures
  - layer heights or volumes
  - gas concentrations
  - optical density of smoke

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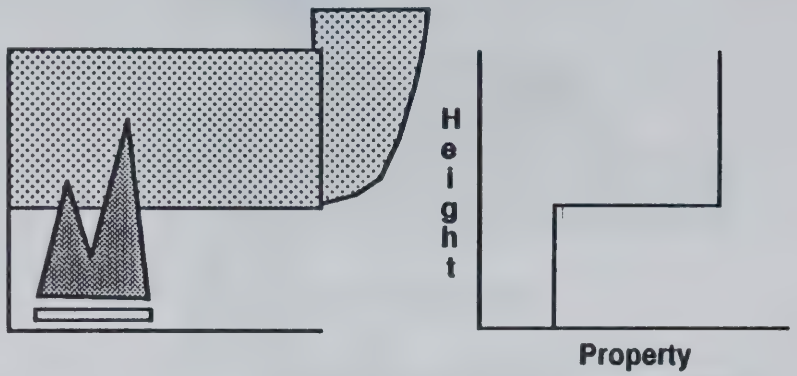
FAST

Zone Model Concept



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FAST

Major Components of the Model

- Mass and energy balances for layers(zones)
- Fluid flows
- Heat transfer
- Combustion and species generation

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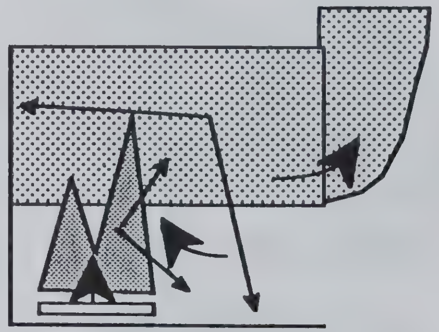
Mass and Energy Balances

Finding Temperatures, Layer Height



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Fluid Flows

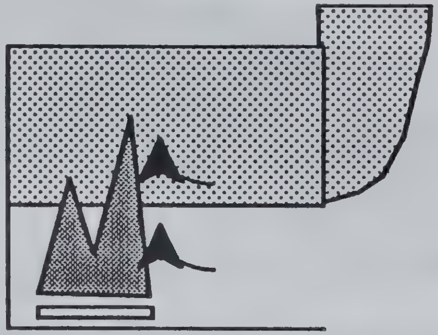
Flow Phenomena in FAST

- Fire plume flows
- Vent flows
- Vent mixing

- All these flows directly affect the temperature, depth, and composition of the layers.

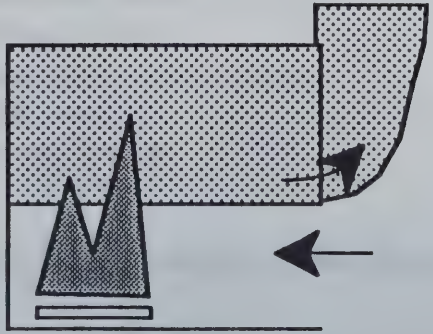
Fluid Flows

Fire Plume Flows



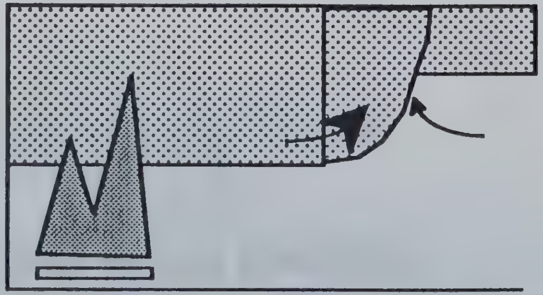
Fluid Flows

Vent Flows



Fluid Flows

Vent Mixing



FAST

Heat Transfer

- Radiation- flame, walls, upper layer
- Convection- walls, layers
- Conduction- walls

- All these heat transfer mechanisms directly affect the layer temperatures.

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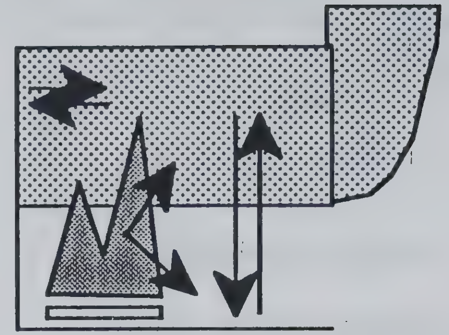
Heat Transfer

Radiation



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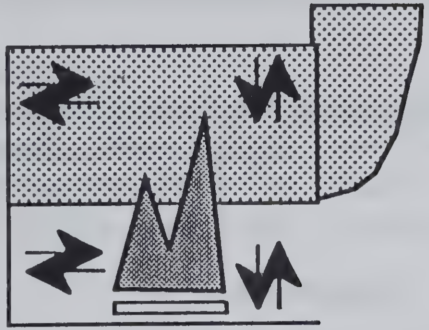
Heat Transfer

Convection



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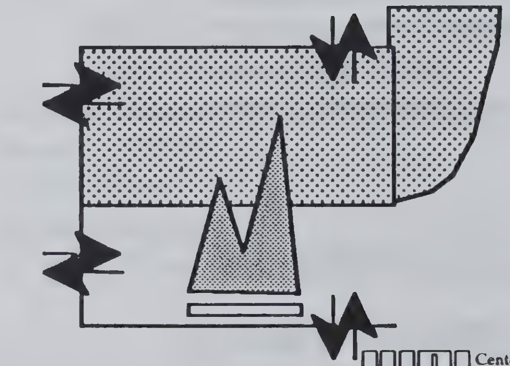
Heat Transfer

Conduction



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FAST

Combustion

- Burning rate
- Species generation
- Species concentration and smoke density

- These phenomena directly affect layer temperature and depth, and directly determine the toxicity of the enviorment.

Combustion

Model

- Two models are included for use:
  Type 1: Unconstrained
  Type 2: Constrained- considers oxygen availability
- Only a sinlge burning item is allowed.

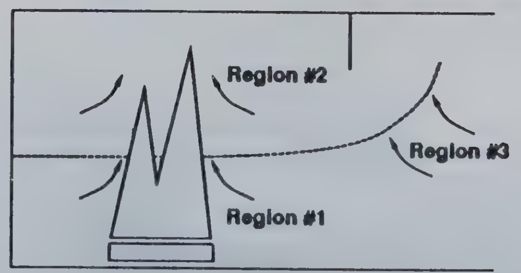
Combustion

Burning Rate

- Fuel volatilization rate is a user input.
- The user must independently predict volatilization rate and anticipate the effect of the room on volatilization.
- This prediction can in part be aided by experimental data.

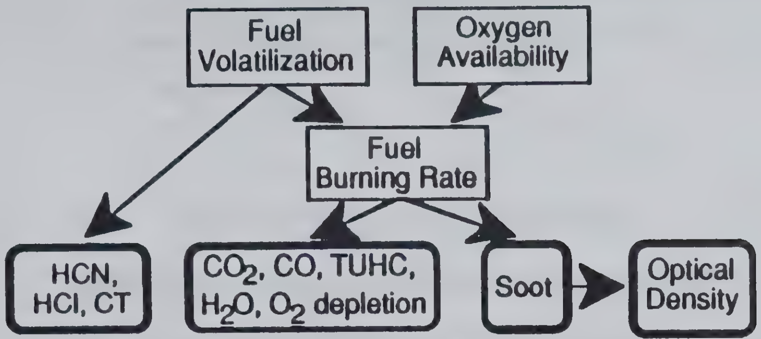
Combustion

Burning Rate



Combustion

Species Generation (Type 2 Only)



Fuel Volatilization

Oxygen Availability

Fuel Burning Rate

HCN, HCl, CT

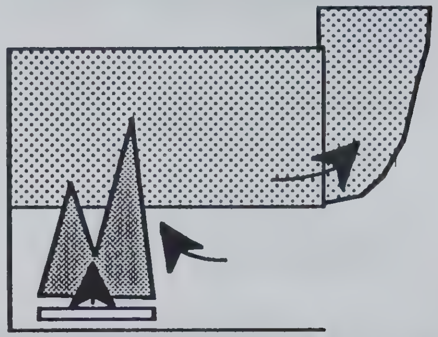
CO_2, CO, TUHC, H_2O, O_2 depletion

Soot

Optical Density

Combustion

Species Concentration



FAST

Fire And Smoke Transport

The role of FAST within the HAZARD I package is to develope predictions of the fire environment in a building due to a single fire within that building.

FAST

Summary

- Mass and energy balances for layers(zones)
- Fluid flows
- Heat transfer
- Combustion and species generation

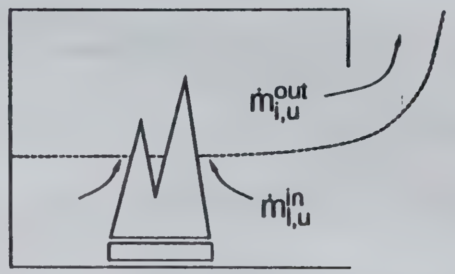
Mass and Energy Balances

Modeling each Zone

- **Equations needed to determine zone properties:**
  - **Temperature: T_u , T_l**
  - **Volume, V_u , V_l**
  - **Room pressure, P**

Conservation of Mass

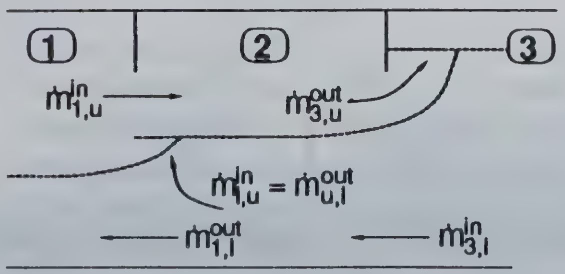
Single Vent Compartment Flows



Conservation of Mass

Multiple Vent Compartment Flows

(Flows relevant to Compartment #2)



Conservation of Mass

The Equations

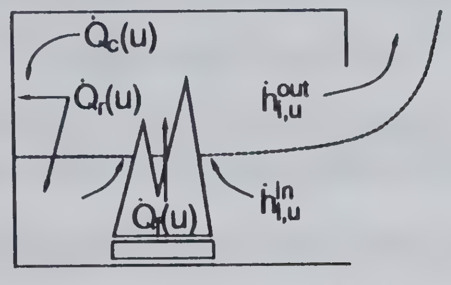
$$\frac{dm_u}{dt} = \sum_{i=1}^{n} \dot{m}_{i,u}$$

$$\frac{dm_l}{dt} = \sum_{i=1}^{n} \dot{m}_{i,l}$$

First Law of Thermodynamics

Conservation of Energy

(Energy transfers relevant to the upper layer)



First Law of Thermodynamics

The Basic Equations

$$\frac{d}{dt}(E_u) + P\frac{dV_u}{dt} = \dot{Q}_u + \dot{h}_u$$

$$\frac{d}{dt}E_l + P\frac{dV_l}{dt} = \dot{Q}_l + \dot{h}_l$$

First Law of Thermodynamics

Heat Losses and Enthalpy Flows (shown for the upper layer only)

$$\dot{Q}_u = \dot{Q}_f(u) + \dot{Q}_r(u) + \dot{Q}_c(u)$$

$$\dot{h}_u = \sum_{i=1}^{n} c_p\, \dot{m}^{in}_{i,u}\, T_i - \sum_{i=1}^{n} c_p\, \dot{m}^{out}_{i,u}\, T_u$$

Auxiliary Relationships

Ideal Gas Law

- **The usual form: $PV = nR_uT$**
- **Moving to mass: $\rho = (n/V)\,MW$**
  $R = R_u/MW$
- **Mass form used: $p = \rho RT$**
- **Note that the molecular wt. of air is used for all gases**

Auxiliary Relationships

Definitions & Closure Assumptions

- **Room Volumes are constant: $V_l + V_u = V$**
- **Pressure is uniform in each room Vertical pressure variations only used for vent flow calculations.**
- **$R = c_p - c_v,\ E_u = \rho_u V_u c_v T_u$**

Pressure Equation

Internal Energy of the Room, E_{rm}

$$E_{rm} = \rho_u V_u c_v T_u + \rho_l V_l c_v T_l$$

Using $P = \rho_u R T_u = \rho_l R T_l$ and $V = V_u + V_l$

$$E_{rm} = \frac{PVc_v}{R};\ \frac{dP}{dt} = \frac{R}{Vc_v}\frac{dE_{rm}}{dt}$$

Pressure Equation

Finding dE_{rm}/dt using the First Law

- **The First Law of Thermodynamics applied to a whole room yields:**

$$\frac{dE_{rm}}{dt} \equiv \$ = \dot{Q}_u + \dot{Q}_l + \dot{h}_u + \dot{h}_l$$

- **Using $c_v = c_p - R$ and $\beta \equiv c_p/R$ gives the final result:**

$$\boxed{\frac{dP}{dt} = \frac{\$}{\beta - 1\ V}}$$

Layer Temperature Equations

The Basic Equations Needed

(Equations for the upper layer shown)

- **First Law of Thermodynamics**

$$\frac{d}{dt}(E_u) + P\frac{dV_u}{dt} = \dot{Q}_u + \dot{h}_u$$

- **Definition of internal energy**

$$E_u = c_v m_u T_u$$

Layer Temperature Equations

The Final Equation

(Shown for the upper layer)

$$\boxed{\frac{dT_u}{dt} = \frac{1}{\beta}\,\frac{T_u}{PV_u}\left(\dot{\varepsilon}_u + \frac{V_u}{(\beta - 1)V}\dot{S}\right)}$$

where $\dot{\varepsilon}_u \equiv \dot{Q}_u + \dot{h}_u - c_p T_u \frac{dm_u}{dt}$

Layer Volume Equations

The Basic Equations Needed

(Equations for the upper layer shown)

$$m_u = \rho_u V_u = \frac{PV_u}{RT_u}$$

- Differentiate with respect to time and use the dp/dt and dTu/dt equations already found.

Layer Volume Equations

The Final Equation

(Shown for the upper layer)

$$\boxed{\frac{dV_u}{dt} = \frac{1}{p\beta}\left(c_p \dot{m}_u T_u + \dot{\varepsilon}_u - \frac{V_u}{V}\dot{S}\right)}$$

Mass and Energy Balances

Assumptions Introduced

- Assumes the zone approach is an accurate description of the temperature profile in a compartment.
- Assumes that the thermodyamic properties of fire gases are well approximated by those of ambient air:
  - molecular weight
  - specific heats

Mass and Energy Balances

Summary

- Balances yield four differential equations for each compartment.
- All other models affect terms in these equations, coupling the phenomena.
- The "Energy Transfers", "Fluid Flows", and "Combustion" sessions will detail these phenomena.

Combustion

Models Available in FAST

- Two combustion models available:
  - Unconstrained- type 1
  - Constrained- type 2
- Unconstrained- fuel is burned without regard for oxygen availability
- Constrained- the availability of both fuel and oxygen are considered.

Combustion

Unconstrained Model (Type 1)

- Heat Release

$$\dot{Q}_f = \Delta h_c \dot{m}_b + c_p (T_v - T_u) \dot{m}_b$$

- Burning rate is assumed equal to fuel volatilization rate, regardless of oxygen availability.
- No species concentration calculations are supported, due to the limitations of the combustion model.

Combustion(Type 2)

General Features

- Combustion is limited by oxygen and fuel availability.
- Chemical species concentrations are calculated.
- Species generation is linearly related to burning rate.

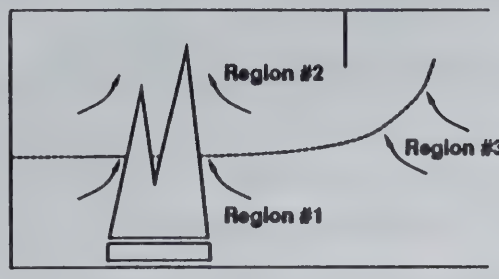
Combustion(Type 2)

Modeling the Rate of Burning

- Combustion can occur in three regions:
  - lower layer
  - upper layer
  - vent plume.
- Combustion is limited in each of these regions by oxygen and fuel availability; i.e. by the fuel supplied and the oxygen entrained.

Combustion(Type 2)

Modeling the Rate of Burning



Combustion(Type 2)

Modeling the Rate of Burning

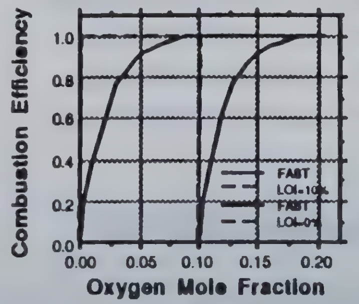
- **Oxygen availability:**

$$\dot{m}_{O_2,\mathrm{avail}} = 0.995 Y_{O_2} \dot{m}_e \left(1 - \exp\left(-10 \frac{X_{O_2} - LOI}{0.207}\right)\right)$$

- **The above is used in all three regions.**

Combustion(Type 2)

Modeling the Rate of Burning



The reduction in burning rate due to oxygen availability is smoothed in FAST.

Combustion(Type 2)

Modeling the Rate of Burning

- **Heat release rate:**

$$\dot{Q}_f = \min\left(\dot{m}_p, \frac{\Delta h_{r,O_2}}{\Delta h_c} \dot{m}_{O_2,\mathrm{avail}}\ \Delta h_c\right)$$

- **Burning rate:**

$$\dot{m}_b = \frac{\dot{Q}_f}{\Delta h_c}$$

Species Generation

General Approach

- CO_2, CO, soot, H_2O generation rate based on burning rate.
- Oxygen depletion based on heat release rate.
- HCN, HCl, CT generation rate based on fuel volatilization rate.

Species Generation

CO_2, CO, Soot

- Model assumes fuel is entirely composed of carbon and hydrogen.
- User specifies:
  - m_H/m_C - ratio of H to C in fuel
  - m_{CO}/m_{CO2} - ratio of generation rates
  - m_S/m_{CO2} - ratio of generation rates

Species Generation

CO_2, CO, Soot

$$m_{CO_2} = \dot{m}_b + m_{O_2\,cons} - m_{H_2O}\,\frac{m_{CO_2}}{m_{CO_2,CO,C}}$$

$$\dot{m}_{CO_2} = 1 + \frac{\Delta H_c}{\Delta H_{R,O_2}} - 9\left[\frac{m_H/m_C}{1 + m_H/m_C}\right]\Big)\left(\frac{\dot{m}_b}{1 + \frac{m_{CO}}{m_{CO_2}} + \frac{m_S}{m_{CO_2}}}\right)$$

$$\dot{m}_{CO} = m_{CO_2}\left|\frac{m_{CO}}{m_{CO_2}}\right|$$

$$\dot{m}_S = m_{CO_2}\left|\frac{m_S}{m_{CO_2}}\right|$$

Species Generation

Water Generation

$$\dot{m}_{H_2O} = 9\,\dot{m}_b\,\frac{\frac{m_H}{m_C}}{1 + \frac{m_H}{m_C}}$$

- Water is assumed to be the only hydrogen containing product of combustion.

Species Generation

TUHC Generation

$$\dot{m}_{TUHC} = \dot{m}_v - \dot{m}_b$$

- Total unburnt hydrocarbons(TUHC) are assumed to only result from the lack of oxygen availability.

Species Generation

Oxygen Depletion

$$\dot{m}_{O_2} = -\frac{\dot{Q}_f}{\Delta h_{r,O_2}}$$

- This expression is accurate to within 10% in most cases.

Species Generation

HCN , HCl , CT Generation

$$\dot{m}_{HCN} = \Psi_{HCN}\,\dot{m}_v$$

$$\dot{m}_{HCl} = \Psi_{HCl}\,\dot{m}_v$$

$$\dot{m}_{CT} = \Psi_{CT}\,\dot{m}_v$$

- Generation rates of these species are modeled as not depending on burning rate..

Species Concentration

Conservation Equation

$$\frac{dm_{j,u}}{dt} = \sum_{i=1}^{n} Y_{j,i}\dot{m}_{i,u}^{in} - \sum_{i=1}^{n} Y_{j,u}\dot{m}_{i,u}^{out} + \dot{G}_{j,u}$$

- Species conservation equations follow the mass conservation law, with the addition of the generation term.
- Losses of species to wall surfaces is not considered.

Optical Density

Relating OD to Soot Concentration

$$OD[1/m] = 3300[m^2/kg]\ C_s[kg/m^3]$$

- Model of Seader and Einhorn for flaming combustion.
- C_s is the mass concentration of soot.
- OD will be related to visibility.

Combustion

Limitations

- Burning rate calculations
- Vent flame model
- Species generation models

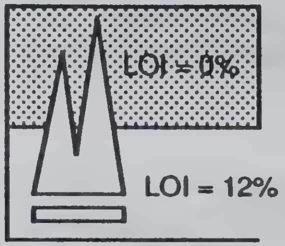
Combustion Model Limitations

Burning Rate Calculations

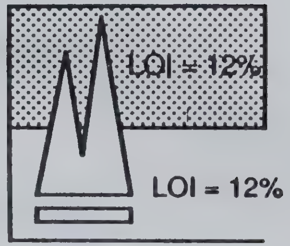
- Model assumes that the oxygen concentration at which extinction occurs is the same in both layers.
- Normal gas phase LOI is about 12% by volume, but this does not hold in two layer combustion conditions.

Combustion Model Limitations

Burning Rate Calculations



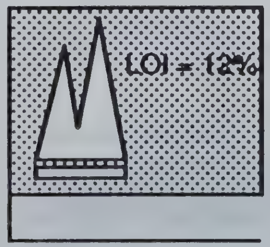
Experimental Data



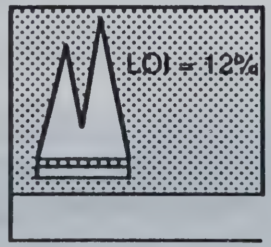
FAST Model

Combustion Model Limitations

Burning Rate Calculations



Experimental Data



FAST Model

Combustion Model Limitations

Burning Rate Calculations

- Fuel volatilization is user specified, i.e. there is no influence of radiative feedback from the upper layer or the flame.
- Only one burning object is included in the model.

Combustion Model Limitations

Vent Burning

- Model requires that the upper layer temperature exceed a user specified temperature for burning.

  Default: $T_{Ig} = T_{pyrol} + 100K$
- Model allows an arbitrarily low concentration of TUHC's to burn.
- The above concepts have not been validated and contradict available data.

Combustion Model Limitations

Vent Burning

- Model allows vent burning, but no burning at the interface in the room.
- Vent flame is assumed to be able to completely burn out the TUHC, if sufficient air is entrained.

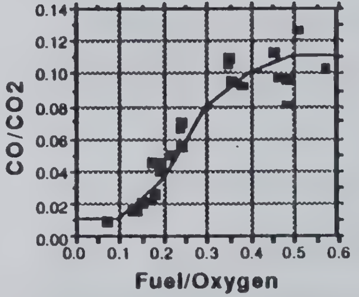
Combustion Model Limitations

CO2 . CO , Soot Generation

- Model utilizes user specified time varying yields, though yields are known to vary with fuel to air ratio. This means user must adjust yield inputs to reflect this phenomena.
- Model assumes fuel is entirely composed of carbon and hydrogen.

Combustion Model Limitations

CO_2 . CO , Soot Generation



- CO/CO_2 ratios vary by an order of magnitude.
- $Soot/CO_2$ ratios variations are not documented.

Combustion Model Limitations

Oxygen Depletion

- Model assumes that if required, all available oxygen is used.
- 0-6% oxygen may exist in the upper layer under fuel-rich conditions, depending on the fuel.

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Combustion Model Limitations

HCN Generation

- Model assumes that a constant yield can describe HCN generation, based on fuel volatilization rate.
- No data is available for the variations in HCN generation with fuel/oxygen ratio.

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Combustion Model Limitations

Optical Density

- Seader and Einhorn model is not universally accepted; constant may vary by a factor of two or more.
- Optical density calculations depend on the soot concentration. All soot production errors affect OD and soot deposition is assumed zero.

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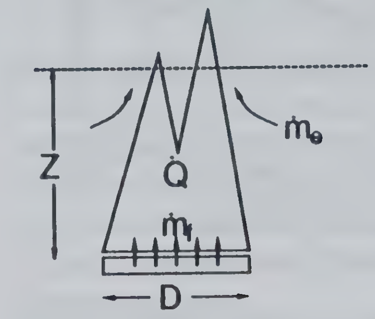
Fluid Flows

Flow Phenomena in FAST

- Fire plume flows
- Vent flows
- Vent mixing

Fire Plumes

Definition of Terms



$$\dot{Q} = \dot{m}_f \Delta H_c$$

$$\dot{m}_p = \dot{m}_e + \dot{m}_f$$

Fire Plumes

The Model

McCaffrey : Units [m,kW, kg/s]

- Continuous flaming: $0.00 < Z/\dot{Q}^{2/5} < 0.08$

  $\dot{m}_p = 0.011Q (Z/Q^{2/5})^{0.566}$
- Intermittent flaming: $0.08 < Z/\dot{Q}^{2/5} < 0.20$

  $\dot{m}_p = 0.026\dot{Q} (Z/\dot{Q}^{2/5})^{0.909}$
- Plume: $0.20 < Z/\dot{Q}^{2/5}$

  $\dot{m}_p = 0.124\dot{Q} (Z/Q^{2/5})^{1.895}$

Fire Plumes

Origin of the Model

- Obtained from 0.3 m square methane burner data.
- Heat release rate range: 14-58 kW.
- Flame height range: 0.5-1.0 m
- Flow rates determined from integrating point measurements of average temperature and velocity.

Fire Plumes

Properties of the Model

- No dependence on fuel source size.
- No dependence on combustion efficiency or radiative prop. of fuel.
- Not consistent with the well documented plume law. $m_e = A\dot{Q}^{1/3}Z^{5/3}$
- Effects of crosswinds not considered.

Fire Plumes

Comparison with Other Models

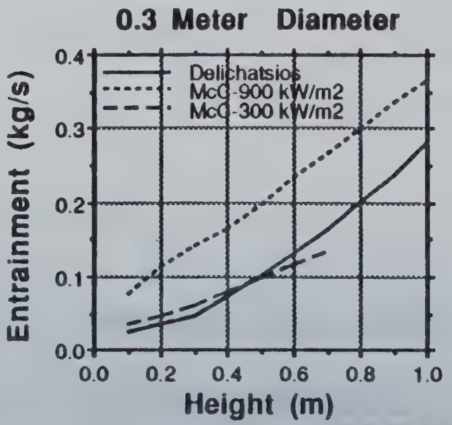
- Within the flame compare with the Delichatsios model.
- Above the flame compare with the point source model with virtual source correction(Heskestad).
- These comparisons are simply illustrative of uncertainty.

Fire Plumes

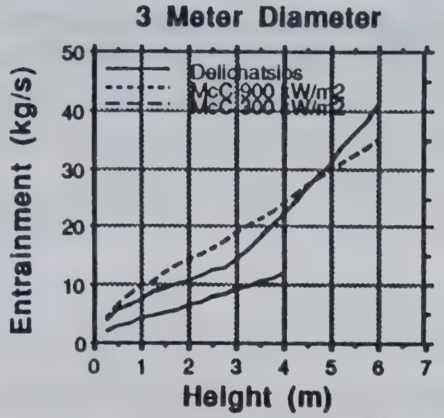
Delichatsios Model

- Model describes entrainment in the flaming region of a fire plume.
- Based on dimensional analysis and data.
- Data obtained by catching the flow in a layer and metering the layer exhaust (Zukoski *et al.*, Beyler)

Entrainment Comparison



Entrainment Comparison



Fire Plumes

Point Source Model

- **Model describes entrainment above the flaming region of a fire plume.**
- **Basic model has been verified by a wide range of investigators over 35 years.**
- **Virtual source correction used to include effect of entrainment in the flaming region.**

Fire Plumes

Point Source Model

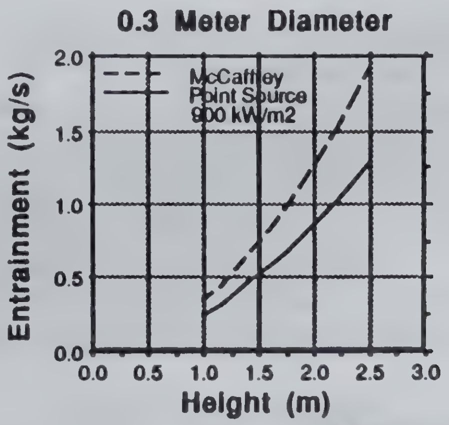
Point Source Model

$\dot{m}_e = 0.076Q^{1/3}Z_V^{5/3}$ [kg/s,kW,m]

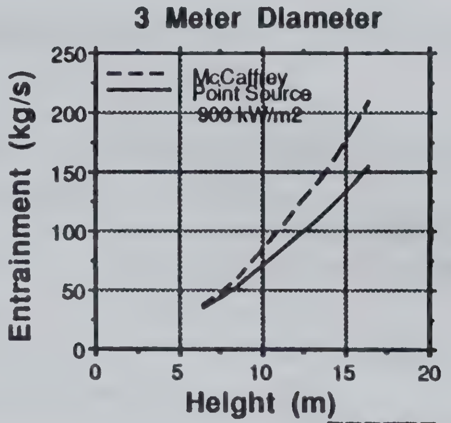
Virtual Source Correction(Heskestad)

$Z_V = Z + 1.02D - 0.083\dot{Q}^{2/5}$ [m,kW]

Entrainment Comparison



Entrainment Comparison



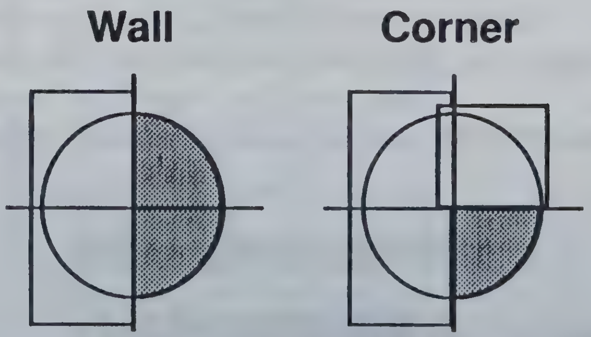
Fire Plumes

Wall and Corner Effects

- Modeled using the "Image Method":
  - Wall Fire(Q) = 1/2 Open Fire(2Q)
  - Corner Fire(Q) = 1/4 Open Fire(4Q)
- Few experimental entrainment data available, but the data indicates that fire must be tight against the wall/corner to see any effect.

Fire Plumes

Wall and Corner Effects



Wall and Corner Effects

A Mathematical Example

- Consider entrainment for a corner fire when the layer interface is above the flame.

$$\dot{m}_{e,c} = \frac{1}{4}\left[0.124\ (4\dot{Q})\left(\frac{Z}{(4\dot{Q})^{2/5}}\right)^{1.895}\right]$$

- In this case the entrainment is about 1/3 of what it would be in the open.

Wall and Corner Effects

Potential Problems

- Errors unknown, too little data available.
- Velocity and Temperature correlations in wall/corner fires differ in form from those in the open(Hasemi & Tokunaga).
- Uncertain when to use wall/corner relations, must be very intimate with the wall.

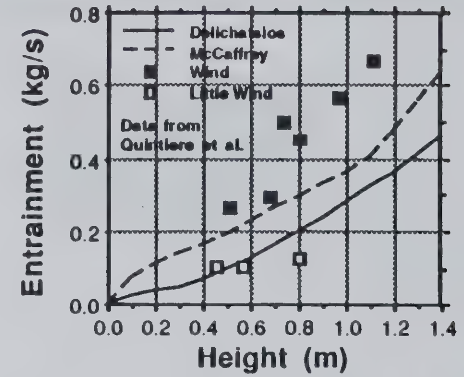
Fire Plumes

Wind Effects

- Winds caused by vent flows may cause fire plumes to lean.
- This can increase the entrainment by a factor of 2-3.

Fire Plumes

The Effect of Crosswinds



Fire Plumes

Error Estimates

- Basic fire plume model
  - Flaming region: ± 100%
  - Plume region: ± 50%
- Wall/corner effects: ?
- Complex fuel geometry: ?
- Wind: can increase entrainment by 2-3 times.
- Overall: uncertainties are large.

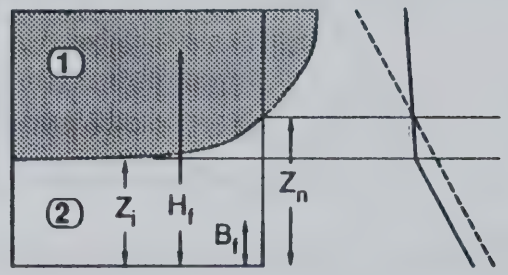
Vent Flows

Properties of the Model

- Buoyancy and pressure driven flows are included.
- No mechanical ventilation or ceiling vents are included.
- Flow is assumed incompressible.
- User specified vent opening during the fire is supported.

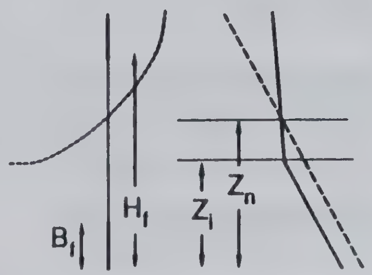
Vent Flows

Typical Vent Flow Schematic



Vent Flows

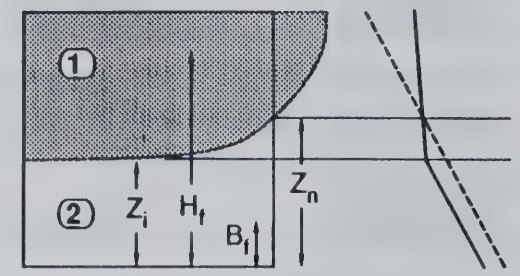
Definition of Terms



- Neutral plane, Z_n
- Layer Interface, Z_i
- Room pressure, P_r(at the floor)
- Soffit height, H_f
- Sill height, B_f

Vent Flows

Example:Find the ΔP at the Soffit



Vent Flows

Finding ΔP at the Soffit

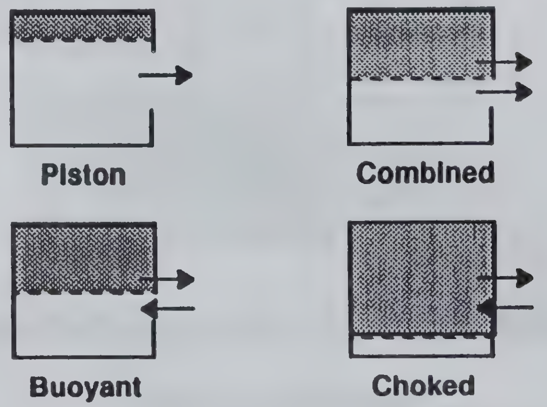
$$P_r(H_f) = P_r(0) - \int_0^{H} \rho g dz$$

$$P_r(H_f) = P_r(0) - \rho_2 g Z_i - \rho_1 g (H_f - Z_i)$$

$$P_o(H_f) = P_o(0) - \rho_{amb} g H_f$$

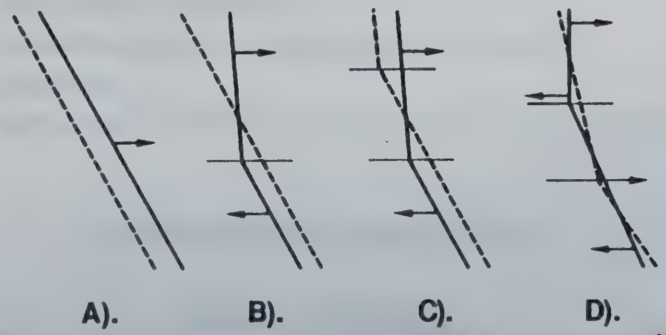
$$\Delta P(H_f) = [P_r(0) - P_o(0)] + (\rho_{amb} - \rho_2) g Z_i + (\rho_{amb} - \rho_1) g (H_f - Z_i)$$

Vent Flow Regimes



Vent Flows

Example ΔP Distributions



Vent Flows

Mass Flow Rate Calculation

- **Mass flow rate:**

$$\dot{m} = \iint_{A} \rho V \, db\, dz = C_d \int_{B_i}^{H_i} \rho V \, dz$$

- **Velocity (from Bernoulli's equation):**

$$V = \sqrt{\frac{2|\Delta P|}{\rho}}$$

Vent Flows

Integrating the Mass Flow Equation

- **Since the ρ profiles are piecewise linear, the ΔP profiles are also piecewise linear. Over each linear segment (i to i+1):**

$$\dot{m}_{i+1} = \operatorname{sign}\left|\frac{\Delta P_{i+1} + \Delta P_i}{2}\right| \frac{2}{3} C_d b \sqrt{2\rho}\,(Z_{i+1} - Z_i) \frac{\left|\Delta P_{i+1}^{3/2}\right| - \left|\Delta P_i^{3/2}\right|}{\left|\Delta P_{i+1}\right| - \left|\Delta P_i\right|}$$

Vent Flows

Integrating the Mass Flow Equation

- **With the ΔP profiles determined and the mass flows through each linear segment known, the flows to and from each layer are tallied to give all the required flow rates.**

Vent Flows

Mass Flow Details

- **Discharge Coefficient, C_d=0.7**
- **The outside pressure used in calculations includes wind effects.**
- **Effect of incompressible flow assumption?**
- **To which layer will the vent flows go?**

Vent Flows

Wind Effects

- The normal external pressure is specified by the user at a reference location and hydrostatic variation are calculated by FAST:stack effect works.
- This pressure is modified by the wind conditions.

Vent Flows

Wind Effects

- The normal wind conditions are specified as:

$$V_{wind} = V_{ref}\ \frac{Z}{Z_{ref}}\Big)^{p}$$

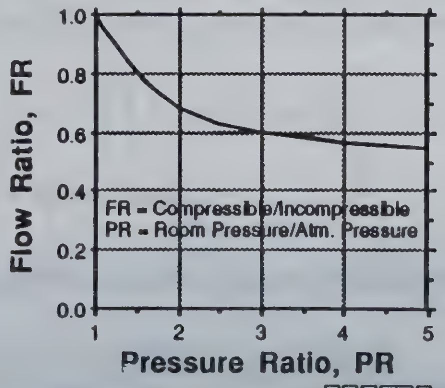
- The wind induced pressure increase is:

$$P - P_o = C_p\left(\frac{1}{2}\rho V_{wind}^2\right.$$

- C_p range: –1 to +1 (see SFPE Hdbk.)

Vent Flows

Effect of Compressibility on Flow



Vent Flows

Flow Destination Selection Rules

- Normal selection rules:
  upper layer → upper layer
  lower layer → lower layer
- Exceptions:
  If T_l(source)>T_u(destination),
  flow goes to the upper layer.
  If T_u(source<T_l(destination),
  flow goes to the lower layer.

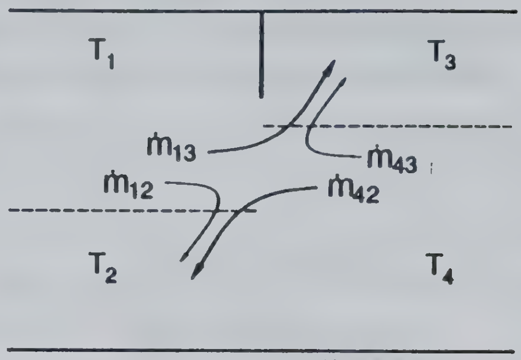
Vent Flows

Vent Mixing

- Mixing of upper and lower layer gases can occur as a result of the vent flows.
- Lower layer air can be entrained into the upper layer due to the plume formed at a vent.
- Similarly, upper layer gases may contaminate the lower layer.

Vent Mixing

Flow Patterns



Vent Mixing

The Basic Approach

- The vent plume is modeled using the McCaffrey model used for the fire.
- A virtual source correction is added to account for the vent flow itself.
- The use of the McCaffrey model for vent mixing has not been formally validated.

Vent Mixing

The McCaffrey Plume Model

- Continuous flaming: $0.00 < Z/\dot{Q}^{2/5} < 0.08$

  $\dot{m}_p = 0.011Q\,(Z/Q^{2/5})^{0.566}$
- Intermittent flaming: $0.08 < Z/Q^{2/5} < 0.20$

  $\dot{m}_p = 0.026\dot{Q}\,(Z/\dot{Q}^{2/5})^{0.909}$
- Plume: $0.20 < Z/\dot{Q}^{2/5}$

  $\dot{m}_p = 0.124Q\,(Z/Q^{2/5})^{1.895}$

Vent Mixing

Modifying the Model

- Need to find equivalent Q and $(Z/Q^{2/5})$ for use in the model.
- The equivalent heat release rate is:

$$\dot{Q}_E = c_p(T_1 - T_4)\dot{m}_{13}$$

Vent Mixing

Modifying the Model

$$\frac{Z_{vp}}{Q_E^{2/5}} = \frac{Z_3}{Q_E^{2/5}} + \frac{Z_v}{Q_E^{2/5}}$$

- The LHS is the equivalent $(Z/Q^{2/5})$ we need for use in the model.
- The RHS is the vent plume and the virtual source, respectively.

Virtual Source

- Find the virtual source by inverting the entrainment model, using the mass and energy from the vent flow.

$$\frac{Z_v}{\dot{Q}_E^{2/5}} = 90.9\frac{\dot{m}_{13}}{Q_E}^{1.76} \quad \text{if } 0.00 < \frac{Z_v}{\dot{Q}_E^{2/5}} < 0.08$$

$$\frac{Z_v}{\dot{Q}_E^{2/5}} = \left(38.5\frac{\dot{m}_{13}}{\dot{Q}_E}\right)^{1.10} \quad \text{if } 0.08 < \frac{Z_v}{\dot{Q}_E^{2/5}} < 0.20$$

$$\frac{Z_v}{\dot{Q}_E^{2/5}} = \left(8.10\frac{\dot{m}_{13}}{\dot{Q}_E}\right)^{0.528} \quad \text{if } 0.20 < \frac{Z_v}{\dot{Q}_E^{2/5}}$$

Vent Flows

Vent Mixing

Using the $\dot{Q}_E$ and $\frac{Z_v}{Q_E^{2/5}}$ now found from the vent flow conditions, the total plume flow , $\dot{m}_p$, can be found using the McCaffrey model.

The entrained flow is $\dot{m}_e = \dot{m}_p - \dot{m}_{13}$

Vent Flows

Vent Mixing

- Vent mixing for lower layer flows are handled the same but the plume is inverted, leading to a contaminated lower layer.
- These vent mixing models are very crude and have not been validated.

Vent Flows

Vent Mixing

- These vent mixing models are very crude and have not been validated.
- Since this is the only way for products of combustion to reach the lower layer, if the individual is in the lower layer the results will be very sensitive to the vent mixing model accuracy.

Heat Transfer

Mechanisms

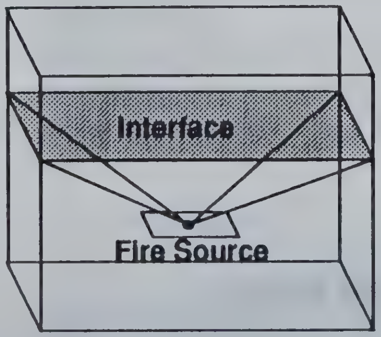
- Radiation: flame, walls, upper layer
- Convection: walls, layers
- Conduction: walls

Radiation

Review of Basic Model

- Bounding surfaces and upper layer are gray.
- Lower layer is transparent in wall/layer interchange calculations.
- Flame radiates to the upper layer and to walls.
- No radiation interchange between rooms.

Flame Radiation

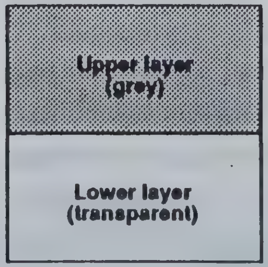


- Flame Radiation:

  $\dot{Q}_{f,r} = \chi_r \dot{Q}_f \; ; \; \chi_r = 0.0$

- Radiation split between upper and lower regions (see figure).
- No Radiation lower layer.

Enclosure Radiation



Two surfaces,one layer included.

A_{upper} = ceiling, upper wall and vent

A_{lower} = floor, lower wall and vent

A_d = interface area

Enclosure Radiation

Upper Layer Radiation Properties

- **FAST uses upper layer gas emissivity, $\varepsilon_g = 0.5$.**
- **The following model more correctly portrays the actual physics.**

Emissivity	$\varepsilon_g = 1 - \exp -kL_m)$
Extinction Coefficient	$k = f(\text{soot}, CO_2, H_2O \text{ conc.})$
Mean Beam Length	$L_m = 4V/A = 4V/(A_{upper} + A_d)$

Enclosure Radiation

Wall Radiation Properties

- **Radiation model uses two surfaces, while conduction/convection use four.**
- **Rad. model uses the maximum emissivity and temperature of wall/ceiling & wall/floor.**

Convection Heat Transfer

Model Properties

- **Convection between layers and adjacent bounding surfaces calculated.**
- **Natural convection expressions used.**
- **Upper wall, lower wall, ceilings, and floors considered separately.**

Convection Heat Transfer

Model Equations

$$\dot{Q}_c = h_c T_g - T_w A_w$$

$$h_c = \frac{k}{L} C_o (Gr Pr^{1/3}$$

$$= \frac{k}{\sqrt{A_w}} C_o \left(\frac{g A_w^{3/2} |T_g - T_w|}{\nu^2 T_g} 0.72 \right)^{1/3}$$

k and ν are functions of temperature

Convection Heat Transfer

Effect of Orientation

Orientation	Coefficient, Co	Condition
Vertical	0.13	all
Ceiling	0.21	Tg > Tw
	0.012	Tg < Tw
Floor	0.012	Tg > Tw
	0.21	Tg < Tw

Convection Heat Transfer

Problems and Limitations

- **Ignores forced convection aspects of compartment flows, e.g. plume, ceiling jets, door jets, etc.**
- **Typical values of heat transfer coefficient:**

FAST: 10 W/m^{2}K

FIRST: 50 W/m^{2}K

Detailed Calculation: 100 W/m^{2}K (Beller, WPI MS Thesis 1987)

Conduction Heat Transfer

Energy Transfer through Walls

- Conduction through ceiling, upper wall, lower wall, and floor considered.
- 1-D finite difference calculation.
- Up to three layer walls, no voids.
- No conduction between rooms, all walls,floors, ceilings connect to ambient.

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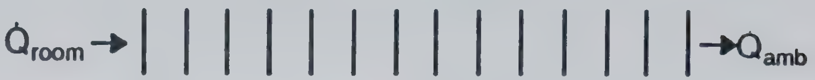
Conduction Heat Transfer

1-D Finite Difference Calculation



$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial x^2}$$

$$T_i^{t+\Delta t}(1+\eta) = \frac{\eta}{2}\, T_{i+1}^{t+\Delta t} + T_{i-1}^{t+\Delta t}\Big| + \Big|T_i^t + \frac{\eta}{2}\, T_{i+1}^t - 2T_i^t + T_{i-1}^t\Big|$$

$$\text{where } \eta = \frac{\Delta t}{\Delta x^2} \frac{k}{\rho c_p}$$

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Conduction Heat Transfer

1-D Finite Difference Calculation

- Crank-Nicholson method used-unconditionally stable method.
- Surface boundary conditions determined from radiation, convection.
- Time step of 0.2 seconds used.
- 36 spatial nodes used in each wall.

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Conduction Heat Transfer

1-D Finite Difference Calculation

- Constant thermal properites used: k, ρ, c_p.
- No moisture effects, no internal radiation.
- Internal layer interfaces have continuous thermal gradients, no contact resistance.
- Adiabatic walls can be specified.
- Layer interface location effects are ignored.

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Heat Flux to Target

Radiative Heat Flux to Individuals

- The incident radiative flux to a surface in the lower layer is available in the output as "On target(W/m^2)".
- This is the incident radiative flux from the upper layer and upper wall/ceiling.
- The flame radiation is not included.
- This variable is used to calculate the effect on people in the lower layer.

FAST Inputs

Fire Scenario Definition

- Fire
- Building
- Occupants

Focus on elements of each which are variable.

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Fire Scenario Definition

The Fire

- Fuel item(s) involved
- Location of fire
- Character of ignition and growth

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CLB-SCEN1-2

Fire Scenario Definition

The Building

- Condition of doors and windows.
- Automatic fire protection
- Wind

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Fire Scenario Definition

The Occupants

- Number and location of occupants
- Capabilities, social characteristics of occupants
- Awake/sleeping - familiar/unfamiliar with surroundings.

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The Fire

Types of Information

- Contents use data(items expected and location)
- Contents fire performance data
- Statistical data(where and how fires start)

The Fire

Contents

- Normal building contents and distribution.
- Inappropriate contents and distributions which can be anticipated.
- Choice of contents is a function of the purpose of the goals of the analysis.

The Fire

Contents Fire Performance Data

- Ignitability*
- Flame Spread*
- Burning Rate
- Species Generation
- Toxicity

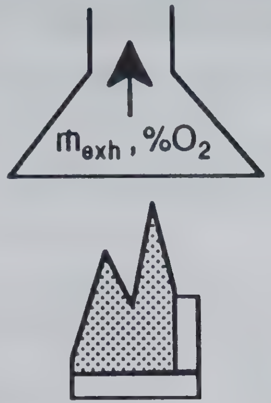
* not directly included in HAZARD I

Burning Rate

Heat Release and Mass Loss Rates

Methods for determining:
  - large scale calorimetry
  - small scale calorimetry plus empirical methods
  - empirical methods based on generic furniture properties
  - room fire tests

Large Scale Calorimetry



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Large Scale Calorimetry

Features

- Full scale testing possible for most items
- No radiative feedback as might occur in room environment
- Free burn combustion- no oxygen limitations

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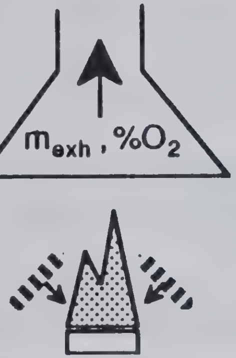
Small Scale Calorimetry



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Small Scale Calorimetry

Features

- Includes effect of radiation on burning rate.
- Does not use actual geometry of item.
- Free burn combustion- no oxygen limitations
- Cannot be used directly without empiricisms.

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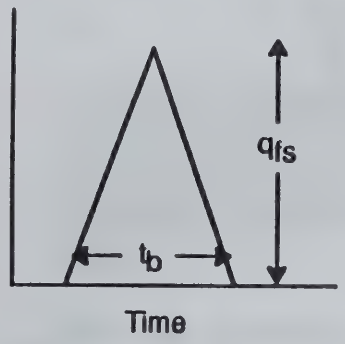
Small Scale Calorimetry

Upholstered Furniture Empiricism



$$t_b = \frac{C_e\, m\, \Delta h_c}{\dot{q}_{fs}}$$

where

$C_e = \begin{Bmatrix} 1.3 \text{ for wood frames} \\ 1.8 \text{ for metal, plastic} \end{Bmatrix}$

m = combustible mass [kg]

Δh_c = effective heat of combustion [kJ/kg]

Small Scale Calorimetry

Upholstered Furniture Empiricism

$$\dot{q}_{fs}\,[\text{kW}] = 0.63\,[\text{m}^2/\text{kg}]\,(\dot{q}''_{bs})\begin{pmatrix}\text{mass}\\\text{factor}\end{pmatrix}\begin{pmatrix}\text{frame}\\\text{factor}\end{pmatrix}\begin{pmatrix}\text{style}\\\text{factor}\end{pmatrix}$$

where

$\dot{q}''_{bs}$ = rate of heat release [kW/m²] in the cone calorimeter averaged over 180s at an incident heat flux of 25 kW/m²

$\begin{pmatrix}\text{mass}\\\text{factor}\end{pmatrix}$ = combustible mass [kg]

Small Scale Calorimetry

Upholstered Furniture Empiricism

$$\begin{pmatrix}\text{frame}\\\text{factor}\end{pmatrix} = \begin{Bmatrix} 1.66 \text{ for non-combustibles} \\ 0.58 \text{ for melting plastics} \\ 0.30 \text{ for wood} \\ 0.18 \text{ for charring plastics} \end{Bmatrix}$$

$$\begin{pmatrix}\text{style}\\\text{factor}\end{pmatrix} = \begin{Bmatrix} 1.0 \text{ for plain rectilinear construction} \\ 1.5 \text{ for more complex shapes} \end{Bmatrix}$$

Generic Furniture

Empirical Model

$$\dot{q}_{fs}\,[\text{kW}] = 210\,[\text{kW/kg}]\begin{pmatrix}\text{fabric}\\\text{factor}\end{pmatrix}\begin{pmatrix}\text{padding}\\\text{factor}\end{pmatrix}\begin{pmatrix}\text{mass}\\\text{factor}\end{pmatrix}\begin{pmatrix}\text{frame}\\\text{factor}\end{pmatrix}\begin{pmatrix}\text{style}\\\text{factor}\end{pmatrix}$$

where

$$\begin{pmatrix}\text{fabric}\\\text{factor}\end{pmatrix} = \begin{Bmatrix} 1.0 \text{ for thermoplastics} \\ 0.4 \text{ for cellulosics} \\ 0.25 \text{ for PVC or PU films} \end{Bmatrix}$$

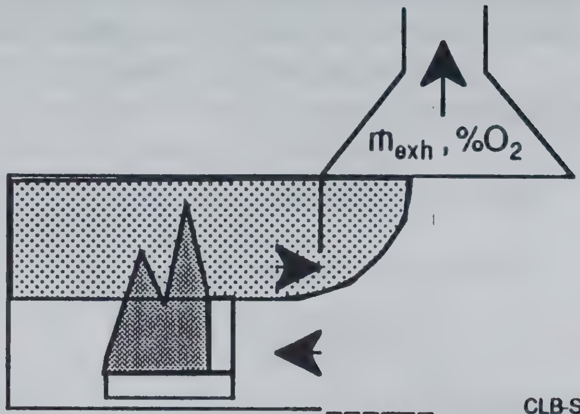
$$\begin{pmatrix}\text{padding}\\\text{factor}\end{pmatrix} = \begin{Bmatrix} 1.0 \text{ for PU or latex foam} \\ 0.4 \text{ cotton batting or neoprene foam} \\ 1.0 \text{ for mixed foam/cotton} \end{Bmatrix}$$

Empirical Models

Limitations

- Only applicable to single furniture items.
- Cone calorimeter model is only applicable if averaged heat release rate exceeds 75 kW/m2.
- Generic model is only valid if [fabric factor]X[padding factor]>0.23
- Items must be similar to the original database items.

Room Fire Tests



Room Fire Tests

Features

- Full scale testing possible for most items.
- Includes radiative feedback from hot layer, but models to interpret the results are lacking.
- Oxygen limitations may act.
- Works best if room is the same room to be used in HAZARD I.

Large Scale Calorimetry

Limitations

- Limited existing database.
- Most data is for "waste basket" type ignition sources. Does ignition source type and location affect burning rate history?
- No inclusion of external radiation effects.
- No data available for complex fuel packages.

Small Scale Calorimetry

Limitations

- Requires empirical models which only exist for simple furniture items.
- Limited existing database of small/large calorimeter results.
- Complex items(geometry and fuel mixes) are beyond current capabilities.
- No theories exist which can predict or represent material behavior.

Generic Empirical Models

Limitations

- Available only for furniture.
- Cannot represent the fire performance of the item since no test data is used.
- Fire performance of the same generic item can vary a great deal.
- Required inputs cannot always be determined accurately.
- Enclosure effects are not included.

Room Fire Tests

Limitations

- Few properly instrumented results are available.
- Includes radiation augmentation for the test enclosure. No simple models exist to allow extrapolation to another compartment.
- Oxygen limitations are included which may or may not act in another room arrangement.

Burning Rate Determination

Limitations

- None of the available methods are universally suitable.
- Preflashover, room and large scale calorimeters are good tools.
- Postflashover, the reliability of even full scale methods is compromised.
- Small scale and generic methods are useful if materials and items are similar to those used to develop the models.

Heat of Combustion

Methods Available

- Oxygen bomb calorimetry
  - combustion of material under high pressure oxygen in a calorimeter.
  - yielding theoretical maximum heat of combustion.
- Oxygen consumption calorimetry
  - requires simultaneous measurement of oxygen consumed and fuel mass lost.
  - yields the effective heat of combustion

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Heat of Combustion

Oxygen Consumption Calorimetry

$$\Delta h_c = \frac{\dot{q}}{\dot{m}_b}$$

- Effective heat of combustion may vary over time due to changes in:
  - the material burning
  - combustion efficiency
  - the fuel volatiles produced
- For use in FAST a single heat of combustion must be selected.

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Mass Burning Rate

Oxygen Consumption Calorimetry

- Remember that the fuel volatilization and burning rates in FAST only include the C and H in the fuel.
- Any experimental weight loss must be reduced accordingly. Failure to do so will affect the heat and species generated.
- Note that in oxygen limited room fire tests there is no good way to determine the burning rate.

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Species Generation

Input Requirements

- H/C
- CO/CO_2
- C/CO_2
- Yields of HCN, HCl, and CT

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Species Generation

Yield of HCN, HCl, CT $\Psi_i = \frac{\dot{m}_i}{\dot{m}_p}$

CO/CO_2 Ratio $\frac{CO}{CO_2} = \frac{\Psi_{CO}}{\Psi_{CO_2}}$

C/CO_2 Ratio $\frac{C}{CO_2} = \frac{\Psi_C}{\Psi_{CO_2}}$

Species Generation

$$\frac{H}{C} = \frac{\frac{2}{18}\Psi_{H_2O}}{\frac{12}{44}\Psi_{CO_2} + \frac{12}{28}\Psi_{CO} + \Psi_C}$$

Statistical Data

Where and How Fires Start

Examples
- **Cause of fire**
- **Ignition scenarios**
- **Area of origin**
- **Material/object first ignited**

Statistical Data

Sources of Information

- **USFA - NFIRS(broad coverage)**
- **NFPA - fire department survey (representative sampling)**
- **WPI - NFIRS analysis capabilities (special analysis of NFIRS data)**

Statistical Data

Particular Areas For Use

- Defining most important scenarios
  - ignition source
  - material involved
  - room of origin
- Defining the expected frequency of each fire scenario

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Defining the Fire

Types of Information

- Contents use data
- Contents fire performance
- Statistical data

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Fire Scenario Definition

Elements

- Fire
- Building
- Occupants

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Fire And Smoke Transport

A Review

We have discussed:
- Role of FAST in HAZARD I
- How to use FAST
- The model and its basis
- Capabilities and limitations
- How to develop FAST input
- How to plot,list FAST output

Fire And Smoke Transport

A Review

In this session we will discuss:
- Validation/overall accuracy of FAST.
- How to critically evaluate FAST results.
- Any remaining questions you have regarding FAST and its use.

Fire And Smoke Transport

Validation

- Validity cannot ever be fully demonstrated.
- As a scientific theory can be shown to be wrong, but can never be shown to be universally correct.
- Examine comparisons of FAST to compartment fire data.

Fire And Smoke Transport

Comparisons with Data

- Two multi-room comparisons are available:
    1. room/corridor gas burner tests
    2. room/corridor/room burner tests
- Oxygen limitations appear not to be reached in these tests.
- Upper layer temperatures are characteristic of preflashover fires.

Fire And Smoke Transport

Comparisons with Data

- Because of the limited range of conditions, many of the model algorithms are not severely tested.
- Many more comparisons need to be made over much broader ranges of conditions.
- Sample comparisons are shown in the following slides.

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CLB-FSTREV1-5

Fire And Smoke Transport

Evaluating Output

In order to evaluate the quality of the results one must know:

- What portions of the model are being used in a particular run?
- If conditions calculated in the run are outside the bounds of prior experiments, either validation tests or submodel testing.

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CLB-FSTREV1-6

Fire And Smoke Transport

Evaluating Output

- What portions of the model are critical to the outcome of the model?
- Are any physical laws being violated by the results?
- Are physical phenomena expected to be important in this case included in FAST and if they are, how well are they modeled?

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CLB-FSTREV1-7

Fire And Smoke Transport

Evaluating Output

- How are approximations in the submodels affecting the results?
- How certain is the input data and does the input data really represent reality?
- Are physical phenomena expected to be important in this case included in FAST and if they are, how well are they modeled?

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CLB-FSTREV1-8

Fire And Smoke Transport

Evaluating Output

- **Be critical of your own results!**

TENAB

Evaluating Effects on People

Hazards Considered

- Narcotic gases
- Thermal hazards
- Other hazards(through CT model)

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TENAB

Hazardous Conditions Endpoints

- Incapacitation- lack of physical ability to move or lack of mental ability to decide to move.
- Lethality

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Toxic Hazards

Narcotic Gases

- These gases interfere with the uptake or use of oxygen by the body.
- Gases considered
  Oxygen depletion(uptake)
  Carbon monoxide(uptake)
  Hydrogen cyanide(cellular use).

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Toxic Hazards

Thermal Hazards

- Damage caused by:
  Skin and lung damage
  Systemic overheating.
- Heat transfer mechanisms:
  Radiation
  Immersion/convection

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Toxic Hazards

Other Hazards

- The CT product is provided to track any other toxic gas desired.
- This model assumed that the toxic behaves according to Haber's Rule.
- Can represent a known toxicant or simply the total apparent effect of all products.

Toxic Hazards

General Modeling Approaches

- N-gas model- a small number of toxic gases are considered; interactions between these gases may be included.
- Individual toxic gas modeling.
- CT model- specific toxic gases are not identified; only the mass of material burned/volatilized and the level of dilution are considered.

Toxic Hazards

General Modeling Limitations

- All approaches are largely based on rodent data; some primate data is available for incapacitation.
- The CT model further suffers from unrepresentative combustion conditions in toxicity tests, and from a lack of specificity.

Toxic Hazards

Model Sources

- NIST researchers- largely based on rodent lethality experiments and literature work.
- Purser- largely based on primate incapacitation experiments and literature work.

Narcotic Gases

Fractional Effective Dose

- Oxygen depletion, carbon monoxide, and hydrogen cyanide are assumed to be additive.

$$FED_{NG} = FED_{O_2} + FED_{CO} + FED_{HCN}$$

$$FED_{NG} \geq 1 \rightarrow \text{effect(incapacitation or death)}$$

Oxygen Depletion

Models

- **NIST Model - Lethality**

$$FED_{O_2} = \int_0^t \max\left(0, \frac{5.8 - C_{O_2}}{9.2}\right) dt$$

Units: concentration [vol. %], time [minutes]

- **Model undocumented and unvalidated.**

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Oxygen Depletion

Models

- **Purser Model - Incapacitation**

$$FED_{O_2} = \int_0^t \exp\left[-7.98 + 0.528\left[20.9 - C_{O_2}\right]\right] dt$$

Units: concentration [vol. %], time [minutes]

- **Based on human experiments under high altitude conditions.**

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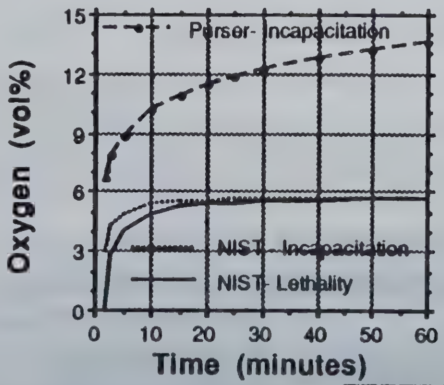
Oxygen Depletion

Model Comparison



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Carbon Monoxide

Models

- **NIST Model - Lethality**

$$FED_{CO} = \int_0^t \frac{\max\left(0, C_{CO} - C_{CO,o}\right)}{80{,}000} \min\left(2, \frac{1}{1 - 0.1C_{CO_2}}\right) dt$$

$$C_{CO,o} = \begin{cases} 1300 & \text{if HCN present} \\ 1700 & \text{if HCN absent} \end{cases}$$

Units: concentration [ppm], time [minutes]

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Carbon Monoxide

Models

- **Purser Model - Incapacitation**

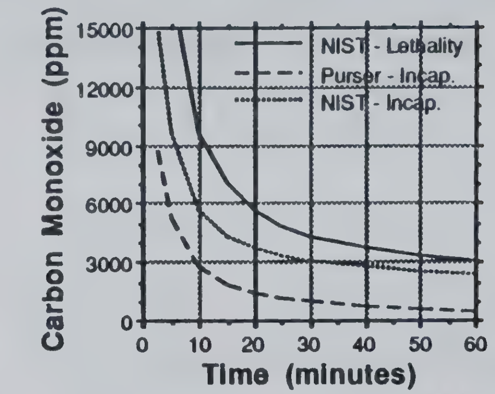
$$FED_{CO} = \int_0^t \frac{8.29X10^{-4} C_{CO}^{1.036}}{30}\, dt$$

Units: concentration [ppm], time [minutes]

- **Assumes individuals are engaged in light activity.**
- **Based on human experiments.**

Carbon Monoxide

Model Comparison



Hydrogen Cyanide

Models

- **NIST Model - Lethality**

$$FED_{HCN} = \int_0^t \frac{C_{HCN}}{3100}\, dt$$

Units: concentration [ppm], time [minutes]

- **Based on rodent experiments.**

Hydrogen Cyanide

Models

- **Purser Model - Incapacitation**

$$FED_{HCN} = \int_0^t \frac{4.4}{185 - C_{HCN}}\, dt$$

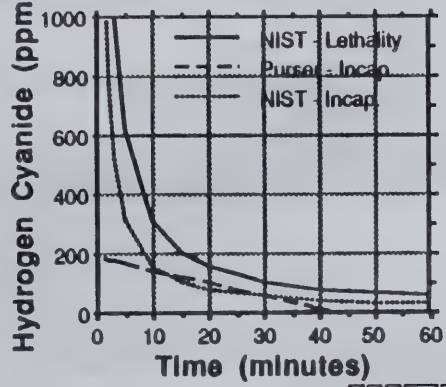
Valid only up to 185 ppm

Units: concentration [ppm], time [minutes]

- **Based on monkey experiments, above 180 ppm subjects were unconscious in a few minutes.**

Hydrogen Cyanide

Model Comparison



Fractional Effective Dose

NIST Model for Narcotic Gases

$$FED_{NIST} = FED_{O_2} + FED_{CO} + FED_{HCN}$$

$$FED_{NG} \geq 1 \rightarrow \text{death}$$
$$FED_{NG} \geq 0.5 \rightarrow \text{Incapacitation}$$

- **Includes CO_2 effect on respiration rate only for CO.**
- **Based on rodent lethality experiments.**

Fractional Effective Dose

Purser Model for Narcotic Gases

$$FED_{Purser} = FED_{O_2} + FED_{CO} + FED_{HCN}) V_{CO_2}$$
$$V_{CO_2} = \frac{\exp(0.2496\, C_{CO_2}[\text{Vol.\%}] + 1.9086}{6.8}$$

$$FED_{Purser} \geq 1 \rightarrow \text{Incapacitation}$$

- **Includes CO_2 effect on respiration rate for CO and HCN, but not activity level.**
- **Based on primate incapacitation tests.**

Thermal Hazards

Thermal Models

- **NIST model- critical exposure temperature:**
  - **Incapacitation: 65°C**
  - **Lethality: 100°C**
- **This model is from literature recommendations.**

Thermal Hazards

Thermal Models

- **Purser model:**

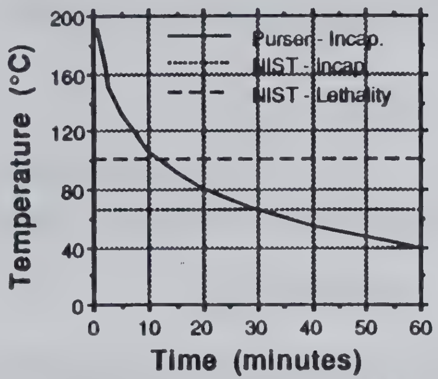
$$FED_T = \int_0^t \exp\left(-5.1849 + 0.0273T\right)\,dt$$

Units: temperature [°C], time [minutes]

- **This model is derived from literature data and includes skin pain(above 121°C) and hyperthermia(below 121°C).**

Thermal Hazards

Model Comparison



Thermal Hazards

Radiation

- **NIST is sending ref on how this is being done- add in when it arrives.**

Material-based Approach

CT Product

- FAST determines the CT for each layer in each room as

$$CT_u = \int_0^t \frac{m_{CT,u}}{V_u} dt$$

- TENAB accumulates the CT exposure for each individual based on the room and layer to which each is exposed.

Toxicological Endpoints

Default Values

Hazard	Incap.	Lethality
Narcotic Gases - NIST (FED1)	0.5	1.0
Thermal - NIST (TEMP1)	65°C	100°C
CT (g min/m3)	450	900
Narcotic Gases - Purser (FED2)	1.0	–
Thermal - Purser (TEMP2)	1.0	–
CO2 - Purser (FED3)	1.0	–

Toxicological Endpoints

Narcotic Gases , Thermal

- These endpoints are the best estimates of knowledgeable experts.
- The values should only be changed on the basis of significant new work.
- Sensitivity analysis can be done by inspecting TENAB output.

Toxicological Endpoints

CT Product

- CT can be used in two ways:

1. As a material based toxicity measure.

2. As a specific toxicant not specifically included in the Hazard I package.

CT Product

Material Based Toxicity

- A CT yield of one is usually appropriate.
- The endpoint is determined from a small scale toxicity test.
- This use assumes the CT (Haber's Rule) is an appropriate model and that the results of the small scale test are relevant to the actual conditions of interest.

CT Product

Specific Toxicant

- The actual species yield should be used as the CT yield.
- The endpoint is determined from a small scale toxicity test.
- This use assumes the CT (Haber's Rule) model for the toxicant and the CT yield model in FAST are appropriate models.

TENAB Limitations

General

- Models are for healthy individuals.
- Sublethal and subincapacitation effects are not included(or known): e.g. toxicants do not change the movement or decision making of the individual.
- Models are based on rodent and primate studies.

TENAB Limitations

General

- Only a limited number of toxicants are considered at all: irritant gases and secondary toxicants are missing altogether.
- Interactions between toxicants are only partially and approximately included: e.g. thermal-narcotic interactions are not included(or well known).

TENAB

Summary

- TENAB provides a limited and nonconservative estimate of the effect of the fire environment on people.
- The Purser measures are far more conservative than the NIST criteria.
- The gases considered and the interactions between gases are very limited.

TENAB

Summary

- The considerable limitations of TENAB are largely due to the state-of-the-art inherent to the problem.
- Limitations not withstanding, TENAB gives a good indication of the hazards to people, though results need serious study and consideration by the user.

EXITT

Model of Occupant Decisions and Actions in Residential Fires

- Deterministic model
- Decision rules define behavior
- Rules consider:
  - Occupant characteristics
  - Building and detectors
  - Fire conditions(smoke only)

EXITT

General Structure of the Model

- Building is represented with nodes and edges(links) between nodes.
- Decision rules govern the path selection
- Speed of travel is determined by the normal travel speed, smoke conditions, and if occupant is assisting another.

EXITT Inputs

Categories

- Building
- Smoke conditions
- Background and alarm noise levels
- Occupant characteristics

EXITT Inputs

Building

- Node locations(room and height)
- Distances between adjacent nodes
- Location and nature of exits(door, window)
- Room heights

EXITT Inputs

Smoke Conditions & Alarm

- Optical densities from FAST
- Location of smoke detectors
- Background noise levels at each node
- Alarm noise level at each node
- Time of activation of detectors or if activated by OD from FAST(detectors activate at OD=0.015 1/m and layer depth of 0.15 m).

EXITT Inputs

Occupants

- Number of occupants
- Age, sex, whether requires assistance
- Node location, normal travel speed
- Whether awake or not, difficulty in waking

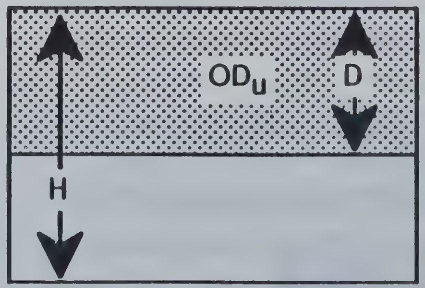
EXITT Decision Rules

Categories

- Aware of fire
- Actions of occupants once aware
- Travel with the building
- Delays, pauses, and action times

Impact of Smoke

Modeling the Psychological Impact of Smoke



- Smoke impact, S, modeled as

  $S = 2\ OD_u\ (D/H)$

- OD_l not used

EXITT Decision Rules

Aware of Fire

- Cues: sound of smoke detector, odor of smoke, visible smoke(if awake).
- Cues are assumed to be additive.
- If cues are marginal, a delayed response is used.

EXITT Decision Rules

Aware of Fire Cues

- Sound of smoke detector
  $X1$ = detector noise(db) - background(db)
- Odor of smoke
  $X2 = S$ for $(H–D)>1.2$ m, $5S$ for $(H–D)<1.2$ m
- Visible smoke(if awake)
  $X3 = S$ for $(H–D)>1.2$ m, $5S$ for $(H–D)<1.2$ m
- Sleeping penalty
  $X4 = 0$ if sleeping, 15 if awake.

EXITT Decision Rules

Aware of Fire Model

- $C = X1 + X2 + X3 + X4$
  If $C > 20$, occupant becomes aware.
- If $20 < C < 37.5$ there is a delay time, T, in becomes aware: $T = 70 – 4(C – 20)$.
- T is calculated at each time step and the earliest time of awareness is used.

EXITT Decision Rules

Occupant Action Priorities

1. Investigate fire.
2. Help occupant in same room.
3. Help occupant in different room.
4. Egress

No reentry of the building is allowed.

EXITT Decision Rules

Action Priority Exceptions

1. Adult females are assumed to rescue an infant before investigating fire.
2. Investigation is not allowed if:
   - occupant has completed investigation
   - occupant has been in a room with moderate(S>0.05) or bad(S>0.4) smoke
   - occupant is awakened by an individual who is not permitted to investigate.

EXITT Decision Rules

Action Priority Exceptions

3. Occupants terminate investigation when they encounter S>0.05 1/m.
4.

Children	Assist Others	Alert Others
Age: >10	yes	yes
Age: 8-10	only in same room	yes
Age: 4-8	no	yes
Age: <4	no	no

EXITT Travel Rules

General Model

- Occupants move from node to node along user defined edges.
- The selection of route to any destination is set by a shortest path algorithm.
- Distance penalties are assessed for window escape paths and smoke laden paths for path selection purposes.
- Smoke can dictate path prohibitions.

EXITT Travel Rules

Smoke Related Rules

- Occupants will use any edge where the lower layer is at least 1.2 m high regardless of the OD_u.
- If the lower layer is less than 1.2 m high, occupants will not use a node with S>0.5.

EXITT Travel Rules

Speed Rules

- Normal travel speed, $V = 1.3$ m/s.
- Travel speed modifiers:
  - $S>0.1$(serious fire), X 130%
  - Occupant assisting another, X 50%
  - $S>0.4$(bad smoke) and lower layer less than 0.5 m(i.e. must crawl), X 60%

EXITT Travel Rules

Delay Time Rules

- Normal initial action delay times are:
  - 6 seconds for awake occupants
  - 10 seconds for sleeping occupants
  - 4 seconds if fire is serious($S>0.1$)
  - 1 second if smoke is bad($S>0.4$).
- Normal delay time to change actions:
  - 3 seconds (e.g. completes investigation and chooses to help another occupant).

EXITT Travel Rules

Delay Times - Occupants not Alone

- In the absence of individuals needing assistance, occupants delay action in the presence of other capable occupants.
- These individuals will not act until a smoke detector sounds or $C>30$ (rather than 20 required when alone).

EXITT Travel Rules

Time to Alert, Wake, or Begin Escape

Person	Delay Time
Alerter	0 s
Alerted	5 s
Waker	5 s
Waken	10 s
Alert & Assist	10 s
Wake & Assist	12 s
Baby (<4 yrs.)	Age + 4 s

Delay times are halved if the alerter, waker, or assister thinks fire is serious($S>0.1$)

EXITT - Summary

- Deterministic model
- Decision rules define behavior
- Rules consider:
  - Occupant characteristics
  - Building and detectors
  - Fire conditions(smoke only)
- Additional detailed documentation available in NBSIR 87-3591 (documentation for a different version of the program- basic, interactive).

MLTFUEL

Combines the Output of Multiple Objects into a Single Fire

- Preprocessor for FAST
- FAST accepts only one fire source.
- MLTFUEL adds contributions from several sources to yield an "equivalent" single source.
- Output manually coupled to FAST

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MLTFUEL

Outputs from MLTFUEL

- Effective heat of combustion
- Effective mass loss rates
- Effective species yields (HCN, HCl, CT)
- Effective CO/CO_2, C/CO_2, H/C

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MLTFUEL

Effective Heat of Combustion

- Arithmetic average:

$$\Delta h_{c,eff} = \frac{1}{n} \sum_{i=1}^{n} \Delta h_{c,i}$$

- Note that the size or mass loss rate is not considered.

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MLTFUEL

Effective Mass Loss Rate

- Mass loss rates are summed:

$$\dot{m}_{eff} = \sum_{i=1}^{n} \dot{m}_i$$

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MLTFUEL

Effective Species Yields

- Effective yields conserve species:

$$\Psi_{eff} = \frac{\sum_{i=1}^{n} \Psi_i m_i}{m_{eff}}$$

MLTFUEL

CO/CO_2, C/CO_2, H/C

- Ratios are derived from effective yields:

$$\left.\frac{CO}{CO_2}\right|_{eff} = \frac{\Psi_{CO,eff}}{\Psi_{CO_2,eff}} , \left(\frac{C}{CO_2}\right|_{eff} = \frac{\Psi_{C,eff}}{\Psi_{CO_2,eff}}$$

$$\left(\frac{H}{C}\right)_{eff} = \frac{\frac{2}{18}\Psi_{H_2O,eff}}{\frac{12}{44}\Psi_{CO_2,eff} + \frac{12}{28}\Psi_{CO,eff} + \Psi_{C,eff}}$$

MLTFUEL

Limitations

- Interaction of multiple burning objects with each other and the room are not considered. User is responsible to assess and include these effects.
- The entrainment of the effective fire source is less than the sum of the individual sources.

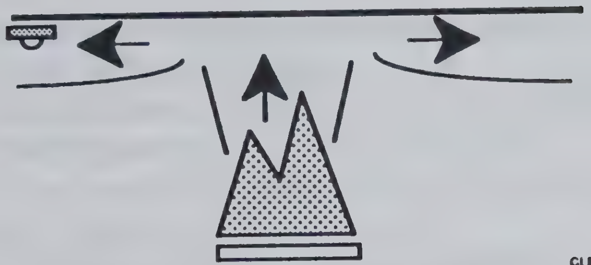
MLTFUEL

Limitations

- Due to the use of a single heat of combustion, energy is not conserved by MLTFUEL. This would only be possible if a time varying heat of combustion were allowed by FAST.
- MLTFUEL does not give an effective fuel height for the effective source fire.

DETACT

Response of Detectors to Quasi- steady Flaming Fires



DETACT

Response of Detectors to Quasi- steady Flaming Fires

- Uses quasi-steady ceiling jet correlations developed by Alpert.
- Models fixed temperature heat detector as a lumped mass.
- Assumes smoke detectors can be modeled as sensitive heat detectors.
- Does not model rate of rise detectors.

Detector Model- Lumped Mass

$$Mc_p \frac{dT_d}{dt} = hA_d(T_g - T_d$$

$$\frac{Mc_p}{h(\sqrt{U_g}|A_d} = \tau \ , \ \tau\sqrt{U_g} = \text{constant} = RTI$$

$$\frac{dT_d}{dt} = \frac{\sqrt{U_g}}{RTI} \ T_g - T_d)$$

$$T_d = T_{d,o} + \int_0^t \frac{\sqrt{U_g}}{RTI} |T_g - T_d| \, dt$$

Detector Model

Response Time Index

- Can be determined from a plunge test or other heated wind tunnel test method.
- Can be estimated from UL/FM listing.

Fixed Temp. Heat Detector

Response Time Index ($m^{1/2} s^{1/2}$)

Listed Activation Temperature of Tested Detector

UL Spacing	128°F	135°F	145°F	160°F	170°F	196°F	FM-All
10 ft.	494	408	324	241	198	120	241
15 ft.	309	235	193	136	110	56	136
20 ft.	204	167	130	87	64	21	87
25 ft.	153	124	98	59	40	---	59
30 ft.	117	99	75	45	---	---	45
40 ft.	88	71	51	22	---	---	---
50 ft.	73	54	37	---	---	---	---
70 ft.	45	30	11	---	---	---	---

Alpert Ceiling Jet Correlations

$$\Delta T_g = \begin{cases} 16.9 \dfrac{\dot{Q}^{2/3}}{H^{5/3}} & \text{for } r/H < 0.18 \\ 5.38 \dfrac{\dot{Q}^{2/3}}{r^{2/3} H} & \text{for } r/H > 0.18 \end{cases}$$

$$U_g = \left. \begin{matrix} 0.95 \dfrac{\dot{Q}^{1/3}}{H^{1/3}} & \text{for } r/H < 0.15 \\ 0.20 \dfrac{\dot{Q}^{1/3} H^{1/2}}{r^{5/6}} & \text{for } r/H > 0.15 \end{matrix} \right\}$$

DETACT User Inputs

- Height from fuel to ceiling, H [m].
- Horizontal distance from fire centerline to the detector, r [m].
- Detector activation temperature, T_{act} [°C].
- Response Time Index, RTI [$m^{1/2}s^{1/2}$].
- Room Temperature, T_{room} [°C].
- Heat release rate, Q [kW] (as time,Q pairs).

DETACT Assumptions

Fixed Temperature Heat Detectors

- Detector located at the maximum ceiling jet temperature and velocity.
- The upper layer and room confinement do not affect the detector environment.
- Convective lumped mass analysis is an appropriate model of the detector.
- Alpert T and U correlations are applicable.

DETACT Assumptions

Fixed Temperature Heat Detectors

- **Flow time from the fire to the detector is insignificant(quasi-steady).**
- **Detector environment is not affected by combustion efficiency or flame radiation.**
- **If the RTI is determined from the UL/FM listed spacing:**
  - **the inversion procedure applied to the test conditions is accurate.**
  - **the T_{act} tested by UL is known.**

DETACT - Smoke Detectors

Methods

- **Assumes at constant ratio: $\Delta T_g / Y_s$.**
- **Assumes a linear relationship between soot concentration and OD.**
- **Assumes that a detector activates at a constant value of OD.**
- **Assumes no restriction of smoke entry to the detector.**
- **The above assumptions allow one to assign a ΔT_g at activation.**

DETACT - Smoke Detectors

Error Estimates

- **OD/ΔT_g = constant**
  - **for a given material: varies by a factor of ten.**
  - **for all materials tested: varied by a factor of 5000.**
- **OD at activation = constant**
  - **for a given material & detector: varied by a factor of ten.**
  - **for all materials & detectors tested: varied by a factor of 1000.**

DETACT - Smoke Detectors

Temperature Rise at Activation

- **Recommendations of Delichatsios and Heskestad (NBS-GCR-77-95):**

Fire Source	Ionization	Photoelectric
Wood cribs	14°C	42°C
Polyurethane	7°C	7°C
Cotton fabric	2°C	28°C
PVC	7°C	7°C

- **Hazard I recommendation: 13°C**

DETACT

Summary

- Useful estimates for fixed temperature detectors and sprinklers.
- Very crude smoke detector model.
- Rate of rise detectors not considered.
- Method only considers flaming fires.

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File Extension Naming Conventions

(from page 3-2 of the Software User's Guide)

.BLD	Building occupant file used as input to EXITT, user generated using the editor
.DAT	Input file for FAST, generated by FAST_IN or editor
.DMP	Unreadable output file from FAST- used to provide input for EXITT and TENAB, as well as FASTPLOT
.EVA	Unreadable output file from EXITT, used to provide input to TENAB
.EXT	Readable output file from EXITT
.FST	Readable output file from FAST
.PLT	Unreadable output file from TENAB, used as input to FASTPLOT
.TEN	Readable output file from TENAB
.TPF	Thermal properties database file for FAST and FAST_IN

FAST_IN

Inputs: .TPF(readable) , .DAT(readable), keyboard
Outputs: .DAT(readable)

FAST

Inputs: .TPF(readable), .DAT(readable)
Outputs: .FST(readable), .DMP(not readable)

EXITT

Inputs: .DMP(not readable), keyboard
Outputs: .EXT(readable), .EVA(not readable)

TENAB

Inputs: .DMP(not readable) , .EVA(not readable), keyboard(con)
Outputs: .TEN(readable), .PLT(not readable)

1/13/90

EXITT BUILDING-OCCUPANT FILE STRUCTURE

File Name Extension : .BLD

Line 1
# FAST compartments, # EXITT nodes

Line 2
Room code numbers
(# of FAST rooms + one = door to outside
# of FAST rooms + two = window to outside)
(Indexed sequentially by node, position in list indicates the node number)

Line 3
EXITT room numbers
(Indexed sequentially by node, position in list indicates the node number)

Line 4
Height of room at nodes
(Indexed sequentially by node, position in list indicates the node number)

Line 5
Height of node above the floor
(Indexed sequentially by node, position in list indicates the node number - note that a person's nose is 5 ft above the node height)

Line 6
Base noise level at each node
(Indexed sequentially by node, position in list indicates the node number)

Line 7
# of smoke detectors

Line 8
Times at which detectors activate
(Indexed sequentially by detector, position in list indicates the detector number - use a –1 to let EXITT activate detector based on the OD of smoke)

Line 9
Node location of detectors
(Indexed sequentially by detector, position in list indicates the detector number)

Line 10
Detector noise level at each node -one line per detector
(Indexed sequentially by node, position in list indicates the node number)

BUILDING OCCUPANT FILE:

# of edges(path segments) connecting nodes

Start node, end node, distance(m)
(One line for each edge(travel path between nodes), indexed sequentially by edge, position in list indicates the edge number)

# of occupants

Age of occupants
(Indexed sequentially by occupant, position in list indicates the occupant number)

Sex of occupants
(Indexed sequentially by occupant, position in list indicates the occupant number: 1=male, 0=female)

Awake or asleep
(Indexed sequentially by occupant, position in list indicates the occupant number: 1=awake, 0=asleep)

Node locations of individuals before the fire
(Indexed sequentially by occupant, position in list indicates the occupant number)

Occupant needs help?
(Indexed sequentially by occupant, position in list indicates the occupant number: 1=yes, 0=no)

Sleeping Penalties
(Indexed sequentially by occupant, position in list indicates the occupant number: 0=normal sleeper or awake, –15= light sleeper, 50= deep sleeper or hearing problems)

Travel speed
(Indexed sequentially by occupant, position in list indicates the occupant number: zero or negative uses default of 1.3 m/s, positive value -> speed, m/s)

BUILDING OCCUPANT FILE:

FIREP9.BLD

6	8										
1	2	3	4	5	6	5	7				
1	2	3	4	5	6	5	3				
2.4	2.4	2.4	5.2	2.4	2.4	2.4	2.4				
0	0	0	0.5	2.3	2.3	2.3	0				
20	20	20	20	20	20	20	20				
2											
-1	-1										
3	5										
95	95	95	95	83	83	83	95				
83	83	83	83	95	95	95	83				
7											
1	2	5									
2	3	5									
3	4	4									
4	5	5									
5	7	3									
6	7	3									
3	8	2									
2											
30	2										
1	1										
0	0										
2	6										
0	1										
0	0										
-1	-1										

See the Software User's Guide pp 4-12 to 4-20 for another sample BLD file and a discussion of BLD files.

BUILDING OCCUPANT FILE:

BUILDING OCCUPANT FILE:

BLD File Worsheet for Lines 2 and 3

BLD File: FIREP9.BLD
# of FAST Rooms(NRM) = 6

EXITT Node #	EXITT Room # BLD Line 3	FAST Room #	EXITT Node # Comment	FAST † Code # BLD Line 2
1	1	1		1
2	2	2		2
3	3	3		3
4	4	4		4
5	5	5		5
6	6	6		6
7	5	5		5
8	3	3	door	7

† - = Fast Room # if not a door or window
= NRM + 1 if node is a door
= NRM + 2 if node is a window

BUILDING OCCUPANT FILE:

BLD File Worsheet for Lines 2 and 3

BLD File:
# of FAST Rooms(NRM) =___

EXITT Node #	EXITT Room # BLD Line 3	FAST Room #	EXITT Node # Comment	FAST † Code # BLD Line 2

† - = Fast Room # if not a door or window
= NRM + 1 if node is a door
= NRM + 2 if node is a window

EXITT Instructions

1. Type the FAST dump file name

   The list of available FAST dump files with the extension DMP is listed on the screen for your convenience.

   The program will ask for a second dump file which you do not want to use, so just hit return.

2. Type the name of the building occupant file (.BLD)

   This is the file which you need to create using the editor. If the screen does not show a BLD file for your case, you have not yet created one and you cannot use EXITT yet.

3. Type the filename for the EXITT output.

   This file is readable and should have the file name extension .EXT.

4. Type the filename for the EXITT dump file.

   This file will be used to communicate with TENAB and should have the extension . EVA.

5. After recieving the dump file name, the program will run.

   Go to the HIS shell (type esc) and use F7 to view the .EXT file to see the results.

TENAB Instructions

1. Type the FAST dump file name

   The list of available FAST dump files with the extension DMP is listed on the screen for your convenience. The program will ask for a second dump file which you do not want to use, so just hit return.

2. Type the name of the EXITT dump file (.EVA) or "con" if you intend to manually define the location and movement of people.

   If you have not yet run the EXITT model, your only options are to use TENAB with manual inputs or to leave TENAB and run EXITT first.

3. Type the filename for the TENAB output.

   This file is readable and should have the file name extension .TEN.

4. Type the filename for the TENAB dump file.

   This file will be used to communicate with FASTPLOT and should have the extension .PLT.

Steps 5-8 are only required if you typed "con" as the source of people movement data earlier.

5. Enter the number of nodes you wish to define.

   Nodes are simply the locations which people can be located in the building.

6. Enter the occupant locations, occupant numbers, time of arrivals at the node, and the node heights

   Remember that the occupant's nose is 5 ft above the node height..

   When you complete all occupant movement instructions simply hit return.

7. Enter the FAST room number for each of the node locations.

8. Alter the default toxicological endpoints if desired.

   We don't recommend you change them in general so just hit enter.

9. The program will run.

   Go to the HIS shell (type esc) and use F7 to view the .TEN file to see the results.

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10. SUPPLEMENTARY NOTES

☐ DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

With the release of HAZARD I, a prototype hazard assessment method and software, the National Institute of Standards and Technology (NIST) has brought to the fire protection engineering community a new generation of hazard analysis capabilities. In order to help HAZARD I users benefit from the software, Worcester Polytechnic Institute (WPI) has developed a five day short course. The short course emphasizes correct use of the software, and how to recognize misuse.

The course has been offered three times to a broad range of students. In general, only those students with an engineering background were able to learn enough about the HAZARD I software to feel that they could continue to learn how to use the software on their own and eventually use it in practice. Nonetheless, virtually all of the students benefitted from the course and found it a worthwhile experience.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

computer models; fire statistics; hazard assessment; manuals; safety factors; training

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